Finite element analysis of flexural properties of recycled concrete beams with different content of nickel slag

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Abstract. Through ANSYS finite element simulation analysis, the influence of different amounts of nickel slag on the mid-span bending moment and deflection of recycled concrete beams under the initial cracking and yielding state is studied. The results show that with the increase of nickel slag content, the flexural performance of recycled concrete beams first increases and then decreases, and there is an optimal nickel slag content. When the nickel slag content is 94kg/m³, the nickel slag has the least effect on the bending performance of the beam. The bending performance of the nickel slag recycled concrete beam is similar to that of the ordinary beam using 100% cement, and it can be used in concrete bending members. Effectively use nickel slag to save resources and protect the environment.

1. introduction
With the rapid development of urbanization in China, a large amount of stainless steel materials are consumed every year. At the same time, about 25 million tons of nickel slag will be produced every year when stainless steel is produced, of which less than 10% is utilized, and the rest are basically piled up or buried in the open air, which has a serious impact on the environment. According to the research data, nickel slag has certain activity and can be applied to the production of concrete. For example, in 2018, Wu Yang found that nickel slag can be used as raw material to produce fine aggregate which can replace cement and has excellent performance through certain physical and chemical way, Zhang Jingxia[1] in 2020Experimental study on basic mechanical properties of nickel slag recycled concrete. The nickel slag concrete with good workability and basic mechanical properties was prepared by changing the mixture ratio. In 2020, Landa-Sanchez found that nickel slag can improve the mechanical properties and durability of recycled concrete. According to the literature investigation and analysis, a series of researches on the basic properties of nickel slag recycled concrete materials have been carried out at home and abroad, and some good results have been obtained. However, there are few researches on the structural members of nickel slag recycled concrete, which need to be further studied.

Therefore, in order to make effective use of nickel slag and reduce environmental pollution, the initial cracks, mid-span bending moment and deflection in yield state of recycled concrete beams with different content of nickel slag are studied by finite element simulation, which provides theoretical reference for future research on flexural performance of recycled concrete beams with nickel slag.
2. scheme design
Six beams with a total length of 1500mm were designed and manufactured, with a net span of 1200mm and a cross-section size of 120 mm× 180 mm. In the beam, 2 C 18 is selected for longitudinal stress reinforcement, 2 C 12 for compression reinforcement and HRB400 grade reinforcement. A10@120 HRB335 steel bar is selected as stirrup, and the elastic modulus of steel bar is 200GPa. In this paper, NRC0 recycled concrete beams without nickel slag are taken as the reference group of specimens, and six groups of recycled concrete beams are designed by changing the nickel slag content of 47kg, 94kg, 141kg, 188kg, 235kg, etc., and all the specimens are analyzed by ANSYS finite element simulation, including the initial crack, bending moment in yield state and deflection in mid-span.

![Figure 1](image_url) Structure diagram of test piece (unit: mm)

![Figure 3](image_url) Reinforcement element

| test-piece number | concrete water cement ratio | Nickel slag content (kg) | Proportion of recycled aggregate (%) | vertical tensile reinforcement | Experimental value of compressive strength (MPa) | modulus of elasticity (×10^4MPa) |
|-------------------|---------------------------|-------------------------|-------------------------------|-------------------------------|-----------------------------------------------|---------------------------------|
| NRC0              | 0.4                       | 0                       | 50                            | 2 C 18                        | 43.21                                         | 2.93                            |
| NRC1              | 47                        | 50                      | 2 C 18                        | 43.15                         | 2.84                                          |
| NRC2              | 94                        | 50                      | 2 C 18                        | 40.14                         | 2.65                                          |
| NRC3              | 141                       | 50                      | 2 C 18                        | 31.22                         | 2.44                                          |
| NRC4              | 188                       | 50                      | 2 C 18                        | 27.05                         | 2.31                                          |
| NRC5              | 235                       | 50                      | 2 C 18                        | 23.14                         | 2.26                                          |

3. finite element simulation
3.1. selection of unit type
Because of the complicated arrangement of reinforcing bars in reinforced concrete beams, the concrete and reinforcing bars are treated as different units by using a separate model. Because the compressive capacity of concrete is far greater than the tensile capacity, SOLID65 element is selected, which can comprehensively consider various concrete material characteristics such as material nonlinearity caused by plasticity and creep, several nonlinearity caused by large displacement, concrete cracking (three orthogonal directions) and nonlinearity caused by crushing. Longitudinal reinforcement and stirrup adopt LINK8 bar element. In order to reduce the stress concentration phenomenon, this paper adopts plane restraint (150mm×100mm) in the support part of the beam and plane uniform load (150mm×100mm) in the three-point loading part. The finite element mesh division of the specimen is shown in Figure 2, and the reinforcement element is shown in Figure 3.
3.2. constitutive model of materials

3.2.1. constitutive relation of recycled concrete with nickel slag
At present, there are few experimental studies on constitutive relation of recycled concrete with nickel slag in China, so the stress-strain curve equation proposed by Professor Zhenhai has been selected in this paper.

\[
y = \begin{cases} 
  ax + (3 - 2a)x^2 + (a - 2)x^2 & 0 \leq x \leq 1 \\
  \frac{x}{b(x - 1)^2 + x} & x \geq 1
\end{cases}
\]

where, \( x = \frac{\varepsilon}{\varepsilon_0} \), \( y = \frac{\sigma}{f_c} \) Professor Xiao Jianzhuang fitted according to equation (1)

\[
a = 2.2(0.748r^2 - 1.231r + 0.975) \\
b = 0.8(7.6483r + 1.142)
\]

Poisson's ratio of concrete is 0.20, and Poisson's ratio\(^2\) of recycled concrete is calculated according to Formula (2)

\[
\nu = 0.21 - 0.0003\delta \quad (\delta \geq 30\%)
\]

\( \delta \) Is the substitution rate of nickel slag.

3.2.2. constitutive relation of reinforcement
In the finite element simulation analysis, the bilinear BGIN follow-up strengthening model is adopted for the reinforcement in the beam, and the corresponding parameters are determined according to GB 50010-2010 Code for Design of Concrete Structures\(^3\), and the constitutive relation (3)

\[
\sigma_s = \begin{cases} 
  E_s\varepsilon_s & \varepsilon_s \leq \varepsilon_y \\
  f_y & \varepsilon_s > \varepsilon_y
\end{cases}
\]

In which, \( E_s \) Is the elastic modulus of reinforcement, \( \varepsilon_y \) Is the yield strain of reinforcement, \( f_y \) Is the yield stress of reinforcement.

Poisson's ratio of tensile reinforcement in beam is 0.3, and Poisson's ratio of compressive reinforcement and stirrup is 0.25.

3.3. constitutive model of concrete material

3.3.1. setting of concrete crushing
Because the engineering structure does not allow great plastic deformation, and the yield point of concrete and other materials is not clear enough, but the failure point is very clear, the relationship
between stress and strain is linear before cracking and crushing, and William-Warnke failure criterion is adopted after cracking and crushing. In the parameter design, the shear transfer coefficient of open cracks is 0.5, that of closed cracks is 0.95, the uniaxial tensile strength is the corresponding to each strength design value, the uniaxial compressive strength is the compressive strength value in Table 1, and all other parameters are the default values.

3.3.2. nonlinear option setting
Complete Newton-Raphson equilibrium iteration is used for nonlinear solution, automatic time step control and linear search are turned on, and all calculations are carried out until the loading process is completed or the calculations cannot converge. Turn on the big deformation switch, the number of loading substeps is 60, the output frequency of the result is Write every substep, and the maximum number of cycles is set to 20 in the Nolinear option. By adopting the displacement convergence criterion, the calculation time is reduced and the convergence accuracy is relaxed to 1.5%.

4. finite element simulation results and analysis

4.1. Analysis of Bending Moment and Deflection in Span of Recycled Concrete Beam with Different Content of Nickel Slag at Initial Cracking

4.1.1. Analysis of Mid-span Bending Moment of Recycled Concrete Beams with Different Content of Nickel Slag at Initial Cracking

Fig. 4 and fig. 5 are stress nephogram and mid-span bending moment diagram of recycled concrete beams with different content of nickel slag at initial cracking. It can be seen from the figure that the mid-span bending moment of NRC0 benchmark beam without adding nickel slag is the largest at the initial cracking, and the mid-span bending moment fluctuates and decreases to some extent with the increase of nickel slag content. That is, compared with the reference group, it decreased by 35.0%, 1.0%, 35.4%, 37.0% and 37.5% from NRC1 group to NRC5 group respectively.

According to literature[4], nickel slag contains SiO2, MgO, CaO, etc., which has certain activity and can replace part of cement. However, in this paper, because the activity of nickel slag is less than that of cement, with the change of nickel slag content, when the nickel slag content is 94 kg/m3, the mid-span bending moment of NRC2 group is the smallest, which is close to the reference group, and the rest groups have greatly reduced the mid-span bending moment.

![Figure 4 stress nephogram of recycled concrete beams with different content of nickel slag during initial cracking](image-url)
4.1.2. Analysis of Mid-span Deflection of Recycled Concrete Beams with Different Content of Nickel Slag at Initial Cracking

Fig. 6 is a mid-span deflection diagram of recycled concrete beams with different nickel slag content at initial cracking. It can be seen from the figure that compared with NRC0 reference beam without nickel slag, NRC1 group decreased by 22.2%, NRC2 group increased by 5.3%, NRC3 group decreased by 17.2%, NRC4 group decreased by 8.7%. Except the NRC2 group, the mid-span cracking deflection of the beam is reduced to varying degrees. It can be seen that adding nickel slag can reduce the mid-span cracking deflection of the beam and improve the bending performance of the beam. This is because nickel slag has micro aggregate effect\cite{5}, and nickel slag can be added as mixed micro powder to fill the internal pores of concrete, which leads to the increase of internal compactness of concrete.
4.2. Analysis of Bending Moment and Deflection of Recycled Concrete Beams with Different Content of Nickel Slag at Yield

4.2.1. Analysis of Mid-span Bending Moment of Recycled Concrete Beams with Different Content of Nickel Slag in Yield

Fig. 7 and fig. 8 are equivalent yield stress nephogram and mid-span yield bending moment diagram of recycled concrete beams with different nickel slag content. It can be seen from the figure that the moment in mid-span of recycled concrete beams in the reference group without adding nickel slag is the largest, and with the increase of nickel slag content, the moment in mid-span increases first and then decreases when the beams yield. That is, compared with the reference group, it decreased by 33.8%, 3.1%, 39.0%, 42.2% and 42.1% from NRC1 group to NRC5 group, respectively. In this paper, when the amount of nickel slag is appropriate, the micro-powder in nickel slag fills the pores of fine aggregate and coarse aggregate, which plays the role of micro-aggregate filling[6] and improves the compactness of concrete. However, with the increase of nickel slag content, the micro-aggregate effect is no longer obvious, but the hydration products in concrete are reduced, the strength of concrete is gradually reduced, and the deformation resistance of concrete in the beam compression zone is also reduced.

Fig. 7 Equivalent yield stress nephogram of recycled concrete beams with different content of nickel slag

Fig. 8 Yield Moment in Span of Recycled Concrete Beams with Different Content of Nickel Slag
4.2.2. Analysis of Mid-span Deflection when Members Yield

Fig. 9 shows the mid-span yield deflection of recycled concrete beams with different content of nickel slag. It can be seen from the figure that compared with NRC0 without nickel slag, NRC1 decreased by 21.0%, NRC2 increased by 2.0%, NRC3 decreased by 22.3%, NRC4 decreased by 19.3% and NRC5. Except NRC2 group, the mid-span cracking deflection of other groups decreased to varying degrees. It can be seen that adding nickel slag can reduce the yield deflection of beams and improve the flexural performance of beams. Adding nickel slag into concrete can fill the tiny pores in concrete, thus increasing the compactness of concrete.

In addition, nickel slag fine powder has certain activity, so adding it into concrete can improve its bending performance; However, with the increase of nickel slag content, the hydration reaction materials in concrete raw materials decrease, the internal voids of concrete increase, the compactness decreases, and the strength of concrete decreases gradually. As a result, the bending stiffness of the beam section decreases and the deflection increases.

Figure. 9 Yield Deflection of Recycled Concrete Beams with Different Content of Nickel Slag in Span

5. Conclusion and Outlook

Through ANSYS finite element simulation analysis, the influence of initial cracks, mid-span bending moment and deflection in yield state of recycled concrete beams with different content of nickel slag is analyzed. The research results show that:

(1) With the increase of nickel slag content, the mid-span bending moment gradually decreases while the mid-span deflection tends to increase. In this study, it is found that the mid-span bending moment and deflection of NRC2 beams with nickel slag content of 94kg/m³ are similar to those of NRC0 reference group.

(2) With the increase of nickel slag content, the bending moment decreases when the beam yields. However, with the increase of nickel slag content, the yield deflection in the mid-span of the beam increases obviously. In this study, when the nickel slag content is 94 kg/m³, compared with NRC0 reference group, the yield bending moment decreases the least and the yield deflection increases the least.

Through the ANSYS simulation analysis of this study, it can be concluded that when the content of nickel slag is 94kg/m³ (the mass ratio of the total cementitious body in 20%), the flexural performance of recycled concrete beams with nickel slag is similar to that of reference beams, and nickel slag can be effectively utilized and environmental pollution can be reduced.

References:
[1] Zhang Jingxia. Experimental study on basic mechanical properties of recycled concrete with nickel slag. Journal of Changchun institute of technology (Natural Science Edition). 2020.21 (2) 11-16.
[2] Zhang Hailong. Experimental study on flexural behavior of steel fiber reinforced high-strength recycled concrete beams. Master's thesis of engineering, Yanbian University. 2016.

[3] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB50010-2010 Code for Design of Concrete Structures. 2011.

[4] Wu Yang. Study on Preparation of Portland Cement from Nickel Metallurgical Waste Residue. Master's Degree Thesis of Engineering, Jiangsu University. 2018.

[5] Ding Tianting, Li Qihua, Chen Shudong. Experimental study on nickel slag concrete. Silicate Bulletin. 2017.2.36 (2) 742-746

[6] Li Hao, Yang Dingyi, Shen Wu, Zhang Shuai, Ge Lijie. Effect of nickel slag on wear resistance of concrete. Silicate Bulletin. 2015.11.34 (11) 3122-3128