SIMULATION OF MECHANICAL BEHAVIOR AND STRUCTURAL ANALYSIS OF GLASS FIBER REINFORCED MORTAR PIPES

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The purpose of this paper is to simulate and investigate the relationship of shell structural characteristics and ultimate bearing capacity (UBC) on glass fiber reinforced mortar (GRP) mortar pipes. In this paper, numerical simulation technology is used to analyze the ultimate strength which is very concerned about the scheme design of GRP mortar pipe. Combined with the static load experiment, the developed finite element numerical model of GRP mortar pipe is validated. The variations of UBC versus ply scheme are investigated for the optimum shell structure as [0/30/90/-30]s. The influence of three main parameters as laying layer, fiber volume ratio and volume ratio of spiral wound are investigated. It is observed that UBC of pipeline increase with increasing the fiber volume ratio and volume ratio of spiral wound layer; however the UBC increases with the pipe layers when the shell structure is within 6 plies and decreases when it is larger than 6 plies.

Keywords: *Glass fiber reinforced plastic mortar pipes; Optimum design; ANSYS; ultimate bearing capacity*

1. Introduction

As one of the three components of the new material industry, fiber-reinforced composite has been widely used in the world due to its good performance. glass fiber reinforced plastic mortar pipes, (GRP mortar or FRPM pipes), that is to say, in the fiber winding process, quartz sand is added into the pipes by using the reinforcing layer, which not only has the characteristics of light weight, high strength and corrosion resistance of ordinary glass fiber reinforced plastic pipes, but also meets the required stiffness of large-diameter pipes.

With rapid development of the glass fiber winding pipe industry, the application field continues to expand, and the pipe manufacturing technology continues to improve, it has become an important industry in the glass fiber reinforced plastic/composite industry. The global production of GRP mortar pipe is increasing rapidly, and GRP mortar pipe is being actively promoted. In Europe, America, Japan, Middle East and other countries, the use of GRP mortar pipe is also increasing rapidly.

The research on the production technology and mechanical properties of GRP mortar pipe started earlier. About 1960, the centrifugal casting technology for producing GRP mortar pipes appeared in Europe. The Owens Corning company of the United States developed the continuous winding technology. It was not until 1980 that fixed length winding technology appeared in Italy. Centrifugal method and continuous winding method were used in Europe and America from 1970 to 1980. However, the pipe rigidity produced by these two processes is relatively low. In 1988, a new standard of glass fiber reinforced plastic pipe[1-2] was successively published abroad, which improved the pipe rigidity produced by these two processes.

The research on the characteristics of glass fiber winding structure is mostly focused on the research of glass fiber reinforced plastic pipe [3-9]. The representative researches on GRP mortar pipes are as follows. In 1981, Ouellette et al. [10] studied and analyzed the design method of GRP mortar pipe, pointing out that according to the bearing requirements and structural characteristics of GRP mortar pipe, it is necessary to calculate the maximum load, bending strength, shear strength and bearing capacity of each layer of the pipe in detail. In 2002, Xia et al. [11] studied the mechanical properties of composite pipes under internal pressure. The stress-strain relationship is obtained. At the same time, it is pointed out that the axial tensile rigidity of the inner surface of the pipe is greater than that of the outer surface. In 2015, Yoon et al. [12] made a long-term performance prediction of GRP mortar pipe subjected to continuous internal pressure. Based on the data of internal pressure test lasting for hours, the failure pressure of GRP mortar pipe in 50 years is predicted by linear regression analysis. The correlation coefficient and variance of the prediction results of the linear regression equation indicates that the linear regression equation has a good applicability in the long-term failure pressure prediction of GRP mortar pipe. Based on the regression ratio between the failure pressure of 6 minutes and 50 years, the long-term performance of GRP tube after 50 years is degraded to the initial performance. In 1996, Gargiulo et al. [13] used four

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failure criteria to analyze the strength of composite pipes, and compared the results under different failure criteria, pointed out that Tsai-Wu tensor criterion can better reflect the failure of materials. In 2010, Diniz et al. [14] selected GRP mortar pipe with diameter and wall thickness for short-term internal pressure failure test. At the same time, the finite element analysis software (FEA) was used to simulate and evaluate the mechanical properties of GRP mortar pipe. In the finite element modeling, the wall of GRP mortar filled tube is considered as an axisymmetric orthotropic material, and the failure pressure predicted by FEA and the average hydraulic failure pressure measured by test are in good agreement, varied from 96% to 98%. In 2014, Rafiee et al. [15,16] analyzed the function failure of GRP pipe under internal hydrostatic pressure, and present a progressive damage model considering the influence of sand layer. Through the experimental study of GRP pipe under hydrostatic pressure, it is observed that the pressure of the first-ply-failure (FPF) and the functional failure (FF) increases linearly with the increase of the sand layer thickness, but the relative difference between them decreases.

A few studies have been conducted on mechanical behavior and manufacturing of GRP pipes[17,18]. In order to resolve this problem, this study proposes the numerical simulation methods to determine ultimate bearing capacity and optimum design by considering the pipe wall manufacturing main parameters as laying layer, fiber volume ratio and volume ratio of spiral wound are investigated.

2. Manufacturing of GRP pipes

2.1 Materials

The main raw materials used in the production of GRP pipe are glass fiber, unsaturated polyester resin, quartz sand, etc.

2.1.1 Glass fiber

Glass fiber is a kind of inorganic fiber with high tensile strength. The chopped glass fibers with dimensions of 40–50 mm (length)×1 mm (width)×0.3 mm (thickness) are typically used. Figure 1 shows three application forms of glass fiber due to different application fields: Glass fiber roving surface mat and chopped mat, respectively.

The glass fiber adopts ECR-2400-906 roving produced by Jiangsu Changhai composite material Co., Ltd. ECR glass is an improved boron free alkali free glass, which is used to produce glass fiber with good acid and water resistance. Its water resistance is 7-8 times better than that of alkali free glass fiber, and its acid resistance is also superior to that of alkali free glass fiber. It is a new variety specially developed for underground pipelines, tanks, etc. The physical properties of glass fiber are shown in Table 1.

2.1.2 Unsaturated polyester resin

Unsaturated polyester resin is one of the most commonly used thermosetting resins. It is a linear polymer formed by condensation of saturated dicarboxylic acid, unsaturated dicarboxylic acid and diol. It is a resin solution with certain viscosity

Table 1

Physical properties of glass fiber

Property	Value	Standard
Length(mm)	12	GB/T 14336[14]
Specific gravity (g/cm^3)	2.5	GB/T 14335[15]
Color	White	-
Melting temperature (℃)	>1500	ASTM-D7138
Tensile strength (MPa)	3100-3400	ASTM-D5035
Ultimate tensile strain (%)	3.3-3.6	ASTM-D5035

Table 2

Properties of unsaturated polyester resin

Appearance	Type	Viscosity /cp.25℃	Thermal deformation temperature /℃	Tensile strength /MPa	Breaking Elongation /%
Light green	O-benzene	400	70	65	3

Table 3

Physical properties of quartz sand

Specific Gravity (g/cm^3)	unit weight (g/cm^3)	Crushing rate (%)	Wear rate (%)	Porosity(%)	Mohs hardness	Sediment percentage (%)	Coefficient of nonuniformity(k80)
2.66	1.75	0.53	0.35	43~47	7.5	=1	=1.8

Note: The common specifications of quartz sand are: 0.5-1mm, 1-2mm, 2-4mm, 4-8mm, 8-16mm, 16-32mm, 10-20 mesh, 20-40 mesh, 40-80 mesh, 80-120 mesh, 100-200 mesh, 200 mesh, 325 mesh.

diluted by cross linking monomer or active solvent, which is called up for short. The physicochemical and mechanical properties are shown in Table 2.

2.1.3 Aggregate

The sand used in the sand layer is quartz sand, which is generally selected to remove dust or other sundries (at present, the purpose is mainly to select the manufacturer), and then after drying, the following technical indicators shall be achieved: (washing, drying, cooling, weighing).

(1) SiO_2 > 95%, should not contain Fe, Co and Mn.
(2) Humidity <0.5%
(3) Particle size: when the diameter of gravel is within 0.3-2.5mm, the proportion of particle size is about 30% for gravel with diameter of 0.3-0.6mm, 30% for gravel with diameter of 0.7-0.8mm, and 40% for the rest.

Quartz sand conforming to the grading shall be mixed evenly. If possible, appropriate coupling agent can be selected to enhance the adhesion with resin and improve the mechanical properties of sand layer. Quartz sand aggregate is made from natural quartz deposit by mining, crushing, washing, screening and other processing (high-purity quartz sand is pickled). Its appearance is a white crystal with multi prismatic shape and spherical shape. It has no impurities, high mechanical strength, stable chemical performance, large pollution interception capacity, long use cycle and good economic benefits. Physical I indexes of quartz sand are shown in Table 3.

2.2 Manufacturing method

2.2.1 Tube wall structure

The traditional GRP pipe wall is composed of two functional layers and one structural layer, that is, the inner layer, the outer protective layer and the structural layer. GRP pipes generally bear certain external pressure while bearing internal pressure, especially the external load borne by underground pipes is large, which includes the upper pressure, ground live load and vacuum pressure during construction, so there is a high demand for pipe rigidity. The usual solution is to increase the wall thickness, that is to say, to meet the rigidity requirements by increasing the amount of GRP, but to do so Therefore, the production cost of GRP is increased greatly, which affects the popularization and use value of GRP. Through mechanical analysis, it is found that the normal stress in the area near the center of the pipe wall is very small under the action of external pressure. Although the shear stress is relatively higher than that in other areas, the shear stress in the whole pipe wall is relatively low, so the material in this area is in a low stress state, so it can completely replace the FRP material near the center of the pipe wall with resin mortar, a low-cost material, so as to form The wall structure of GRP mortar pipe with resin quartz sand core. Since this new type of pipe wall structure can meet the performance requirements of high rigidity of the pipe, the cost is greatly reduced, so that the GRP with sand is more competitive in the market.

2.2.2 Technological process

As one of the earliest and most widely used processing technologies, filament winding technology plays an important role in the production of fiber composite products. The so-called filament winding technology is the production technology that continuous fiber products are fully soaked by resin glue, continuously wound to the core mold according to a certain angle, and finally the products are obtained by curing and demoulding. The winding process is mainly divided into continuous winding and discontinuous winding. In the continuous winding process, firstly, the fiberglass surface felt is wound on the mold, secondly, the inner winding yarn, axial yarn, resin, quartz sand, outer winding yarn, etc. are added, then these fillers are dispersed in the proper position of the mold, finally, a layer of fiberglass surface felt is wound on the outermost layer. Glass fiber reinforced plastic sand pipe is through the continuous circular movement of the steel belt, in the continuous forward core mold, the production process of filament winding, packing compound, adding quartz sand and so on is completed successively. After the completion of

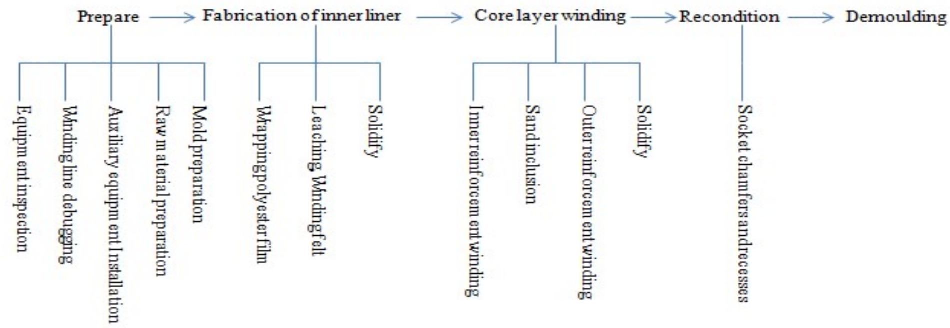

Fig.1 - Continuous filament winding process.

Table 4

Material properties of fiber and resin matrix

Constituent	E/GPa	μ	G/GPa	v_f	$\sqrt{v_f}$
Glass fibre	53.5	0.21	22.11	0.525	0.724569
Resin matrix	2.6	0.31	0.99	0.475	0.689202

Table 5

Performance parameters of single-layer filament wound layer

E_x	E_y	E_z	μ_{yz}	μ_{xz}	μ_{yx}	G_{yz}	G_{xz}	G_{yx}
3.19	3.19	29.32	0.30	0.30	0.26	1.23	1.23	3.22

all processes, the formed pipes shall be transported to the curing area to complete the curing, and finally cut and ground to the required size according to the engineering standard. The complete production line is mechanized flow operation, and the process flow of fixed length winding GRP mortar pipe is shown in Figure 1.

3. Numerical modeling

Combined with the test model, the ANSYS numerical analysis finite element model of GRP mortar pipe is established. Select the SHELL99 element in ANSYS, set the fiber winding layer as orthotropic material, and set the sand layer and inner liner as isotropic material. The material properties of the fiber and resin matrix are given in Table 4. Taking single-layer filament winding layer as an example, the performance parameters of filament winding layer calculated from Table 4. are listed in Table 5.

The main physical property parameters of other layer components are as follows: inner layer: elastic modulus is 6.74GPa, Poisson's ratio is 0.33; sand layer: elastic modulus is 6.4 GPa, Poisson's ratio is 0.33. The model of GRP mortar pipe after constraint and load is shown in Figure 2.

The static load test results of the ultimate bearing capacity of GRP mortar pipe are compared with the ANSYS simulation results, as shown in Figure 3.

It can be seen from Fig.3. that when the radial deformation of GRP mortar pipe is less than 58mm, the sand layer and fiber winding layer work together to resist the pressure, but when the deformation is greater than 58mm, due to the fracture failure of sand layer, all the compressive strength is borne by the fiber layer, resulting in the decrease of compressive strength. As the deformation continues to increase, the fiber layer produces interlayer failure, and the compressive strength gradually decreases. Therefore, when the circumferential deformation is large, the simulation value is lower than the test value, but the overall trend is the same. The error between ANSYS result and test result is very small. It is proved that ANSYS Workbench can be used to analyze the ultimate bearing capacity of GRP mortar pipe.

Fig.2 - Constraint and load diagram.

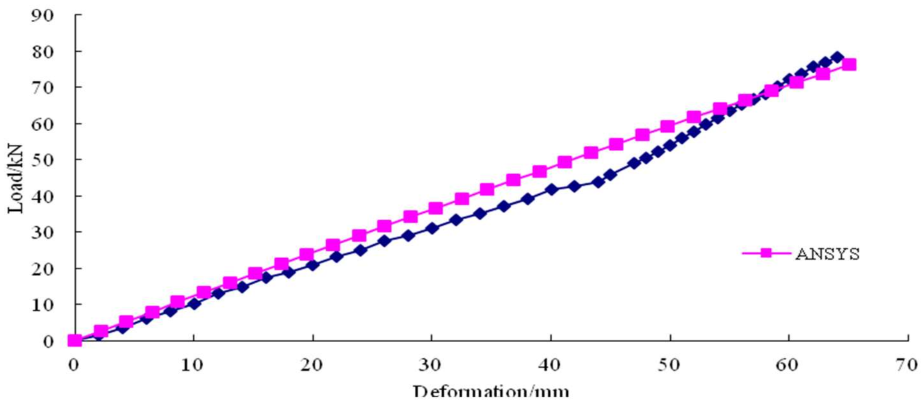

Fig.3 - Comparison of ANSYS simulation value with test value.

Table 6

Calculation parameters of GRP mortar pipe with various layers

Constituents	Five-ply	Six-ply	Seven-ply	Eight-ply	Nine-ply
Circumferential winding ply	4mm	4mm	4mm	4mm	4mm
Sand inclusion	/	/	12mm	/	9mm
Spiral wound ply	/	/	3mm	2mm	2mm
Sand inclusion	/	/	12mm	12mm	9mm
Spiral wound ply	/	3mm	3mm	2mm	2mm
Sand inclusion	18mm	18mm	12mm	12mm	9mm
Spiral wound ply	6mm	3mm	/	2mm	2mm
Sand inclusion	18mm	18mm	/	12mm	9mm
Inner liner	4mm	4mm	4mm	4mm	4mm
Volume ratio of spiral wound ply	12%	12%	12%	12%	12%
Fiber volume ratio	28%	28%	28%	28%	28%
Ultimate bearing capacity（kN）	68.687	78.414	76.160	75.489	71.843

Table 7

Calculation parameters of GRP mortar pipe with various fiber volume ratio

Constituent	Fiber volume ratio				
	27%	31%	36%	40%	44%
Circumferential winding ply	5mm	6mm	7mm	9mm	9mm
Sand inclusion	12mm	10mm	10mm	9mm	9mm
Spiral wound ply	2mm	2mm	2mm	2mm	2mm
Sand inclusion	12mm	14mm	12mm	10mm	10mm
Spiral wound ply	2mm	2mm	2mm	2mm	2mm
Sand inclusion	12mm	10mm	10mm	9mm	9mm
Inner liner	5mm	6mm	7mm	9mm	9mm
Volume ratio of spiral wound ply	8%	8%	8%	8%	8%
Fiber volume ratio	27%	31%	36%	40%	44%
Ultimate bearing capacity（kN）	76.160	82.645	87.604	92.046	98.344

4. Results and discussion

4.1 Influence of laying layer

The laying layers of GRP mortar pipe not only affect the ring stiffness of the pipe, but also affect the ultimate bearing capacity of GRP mortar pipe. In order to study the influence of the number of plies on the ultimate bearing capacity of GRP mortar pipe, other structural parameters are given, and the number of plies is set as five, six, seven, eight and nine, respectively. The ANSYS numerical model is established to simulate the ultimate compressive bearing capacity of these five types of GRP mortar pipe. The calculation results and structural parameters are listed in Table 6.

In order to find the influence of the number of layers on the ultimate bearing capacity of GRP mortar pipe more intuitively, the relationship curve is drawn, as shown in Figure 4.

As shown in Figure 4., the number of layers of GRP mortar pipe wall is within 6 layers, the number of layers of the pipe is basically proportional to the ultimate bearing capacity, which is mainly due to the reasonable laying sequence that enhances the bearing capacity of the pipe; when the number of layers of GRP mortar pipe wall is greater than 6 layers, the extreme bearing capacity of the pipe is declining, which is mainly due to the constant wall thickness and fiber volume of GRP mortar pipe. In the case of too many layers, it means that more winding layers and sand layers with smaller thickness should be set, and the weak bonding stress between layers reduces the overall bearing capacity.

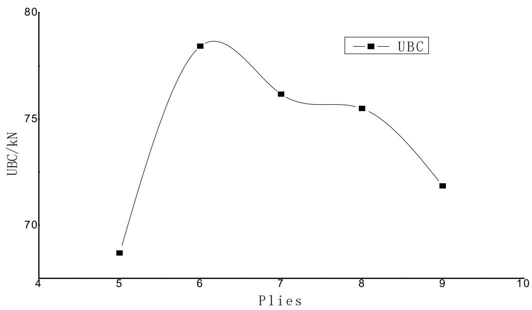

Fig.4 - Curve of ply number and ultimate bearing capacity.

4.2 Influence of fiber volume ratio

Fiber layer is an important part of the structure layer of GRP mortar pipe. Its main function is to bear the external load of the pipe, which has a direct impact on the strength of GRP mortar pipe. Similarly, in the study of the influence of fiber volume ratio on the strength of GRP mortar pipe, other structural parameters are given, only five fiber volume ratios of 27%、31%、36%、40% and 44% are set respectively. The numerical models of these five types of structures are established by ANSYS, and the simulated ultimate bearing capacity and calculated structural parameters are listed in Table 7.

According to the ultimate bearing capacity of the above five structures obtained by ANSYS simulation, the relationship curve between the GRP mortar pipe and the fiber volume ratio is drawn, as shown in Figure 5.

It can be seen from Figure 5 that the ultimate bearing capacity of the pipeline increases with the increase of fiber volume ratio of GRP mortar pipe. Therefore, increasing the fiber volume ratio of GRP mortar pipe can not only improve the ring stiffness of the pipe, but also greatly improve the bearing capacity of the pipe. It also shows that the fiber layer is an important part of the GRP mortar pipe structure layer and an important bearing layer of GRP mortar pipe.

4.3 Influence of volume ratio of spiral wound ply

Spiral wound layer is an important part of structural layer, which mainly bears the load of pipe culvert. Appropriate thickness of spiral winding layer can improve the ring stiffness of GRP mortar pipe. The influence of the volume ratio of spiral wound layer on the bearing capacity of the pipe is studied. The laying layer number of GRP mortar pipe is set as seven layers, the thickness of the pipe is 50 mm, the volume ratio of fiber is 28%, and the volume ratio of the spiral wound layer of 8%、12%、15%、20%、23%, etc as shown in Table 8.

According to the data of the ultimate bearing capacity of GRP mortar pipe from Table 8., the relationship between the volume ratio of GRP mortar pipe and the spiral wound layer of the pipe is drawn, as shown in Figure 6.

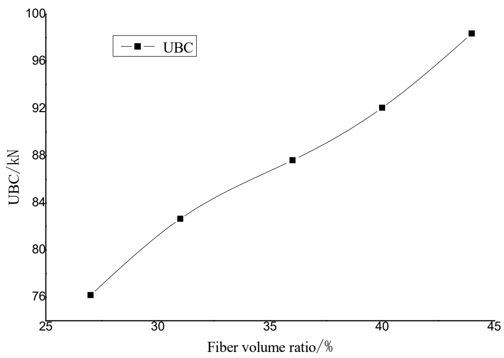

Fig.5 - **C**urve of fiber volume ratio and ultimate bearing capacity.

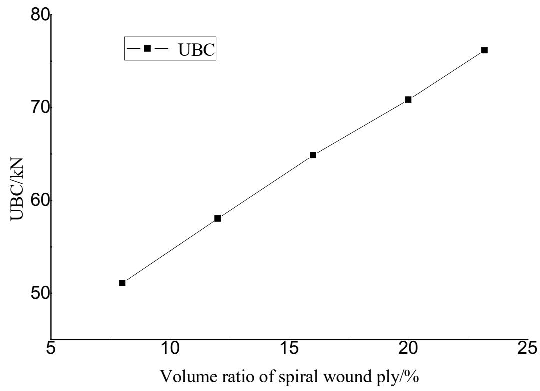

Fig.6 - **C**urve of volume ratio of the spiral wound ply and ultimate bearing capacity.

Table 8

Calculation parameters of GRP mortar pipe with various volume ratio of the spiral wound ply

Constituent	Volume ratio of the spiral wound ply				
	8%	12%	16%	20%	23%
Circumferential winding ply	5mm	4mm	3mm	2mm	1.2mm
Sand inclusion	12mm	12mm	12mm	12mm	12mm
Spiral wound ply	2mm	3mm	4mm	5mm	5.8mm
Sand inclusion	12mm	12mm	12mm	12mm	12mm
Spiral wound ply	2mm	3mm	4mm	5mm	5.8mm
Sand inclusion	12mm	12mm	12mm	12mm	12mm
Inner liner	5mm	4mm	3mm	2mm	1.2mm
Volume ratio of spiral wound ply	28%	28%	28%	28%	28%
Fiber volume ratio	8%	12%	16%	20%	23%
Ultimate bearing capacity（kN）	51.099	57.901	64.849	71.069	76.160

As shown in Fig.6, the ultimate bearing capacity of GRP mortar pipe increases with the increase of spiral wound layer volume, and it is approximately linear. It shows that the spiral wound layer is an important part of the structure which subject the external force. Increasing the volume ratio of the spiral wound layer can obviously improve the strength of the GRP mortar pipe.

5. Conclusions

Ultimate bearing capacity is an important index for the design of GRP mortar pipe. In this paper, the ANSYS simulation results are compared with the experimental data. On the basis of proving the feasibility and accuracy of using numerical simulation technology to analyze the ultimate bearing capacity of GRP mortar pipe, the relationship between the parameters such as the number of pipe layers, fiber volume ratio, spiral winding layer thickness, fiber winding angle and the ultimate bearing capacity of GRP mortar pipe is analyzed, and the optimal structure of GRP mortar pipe wall is obtained. The specific conclusions are as follows:

- Under the premise of keeping other parameters unchanged, the number of pipeline layers is set as five, six, seven, eight and nine layers respectively. The numerical simulation results show that the ultimate bearing capacity is in direct proportion to the number of pipe layers when the pipe wall structure is within 6 layers. When the number of GRP mortar pipe wall layers is greater than 6, the ultimate bearing capacity of the pipe shows a downward trend.
- Glass fiber plays an important role in the mechanical properties of GRP mortar pipe. When studying the relationship between the volume ratio of fiber and the ultimate bearing capacity of the pipe, the volume ratio of fiber to be optimized is set to 27%, 31%, 35%,40% and 45%. The simulation results show that the ultimate bearing capacity of these five kinds of GRP pipes increases with the increase of fiber volume ratio. Therefore, increasing the thickness of fiber ply is an effective way to improve the bearing capacity of GRP mortar pipe.
- Spiral winding layer is not only the strengthening layer of pipeline, but also the main structural layer of pipeline under external load. Therefore, the volume ratio of spiral wound layer is one of the key contents to optimize the structure of GRP mortar pipe culvert with sand. The ultimate bearing capacity of the pipe increases with the increase of the volume ratio of the spiral wound layer, and the relationship is approximately linear. The results show that the spiral wound layer, as an important part of the structural layer, plays a key role in the strength of GRP mortar pipe.

In summary, the factors that affect the service performance of GRP mortar pipe include not only the mechanical properties of the pipe, but also the thickness and overall quality of the pipe. There are different design schemes for the distribution and ratio of fiber ply and sand ply in the structural layer, so that the wall materials with different physical and mechanical properties can be obtained.

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