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Preface

With the vigorous development of highway, more strict requirements have been put forward on the material performance. It is difficult for traditional single material to meet the comprehensive performance requirements and high index requirements. The development of composite materials has become an inevitable trend in civil engineering. With a dozen years of wide application of highway composite materials, there have recently been a large number of scientific research results. Theoretical and technological levels have been further improved. A dozen of years of teaching and research experience has been accumulated in this course. Large materials which are related to composite materials at home and abroad have been collected. Based on the original *Highway Engineering Composite Material and Its Application* edited by Jialiang Yao, Zhigang Zhou, Jiejun Tang of CSUST, this book is compiled and finished.

The basic concept, composite principle and requirements, material properties, mix proportion design, and engineering application of main composite materials used in highway engineering are systematically introduced in this book. The development, definition and classification, strengthening theory, damp-heat effect, interface, design content and methods of composite materials, the compatibility of matrix and reinforcement, and the wettability are mainly introduced in the first chapter. The engineering characteristics, interfacial friction characteristics and their functions, and the main applications of geosynthetics in engineering are mainly introduced in the second chapter. The material and process characteristics, reinforcement mechanism, interfacial properties, the properties, mix proportion design, construction process, and application of steel fiber-reinforced cement concrete in engineering are mainly introduced in the third chapter. The concept and classification of modified asphalt, modifier and modified asphalt pavement performance, the selection of polymer modifier and modification effect evaluation, modified asphalt technical indices and standards, modified asphalt production process, the basic concept, formation mechanism, characteristics, material requirements, mix proportion design process, pavement construction, and quality inspection of Stone Mastic Asphalt are introduced in the fourth chapter. The polymer matrix, polymer concrete, and other applications of polymer in concrete are mainly introduced in the fifth chapter. The concrete pavement, functional layer composite materials of asphalt pavement, and preventive maintenance engineering materials of pavement are introduced in the sixth chapter.

It can be used as a textbook for postgraduates or a textbook of optional course for undergraduates. It can also be used as a training textbook and a reference book for technical personnel with foreign projects in engineering.

Due to our limited level and the rapid development of highway composite materials, some mechanisms are still to be studied. Please kindly correct it if there is any mistake.

The book is supported by School of Traffic and Transportation Engineering of CSUST, and National Natural Science Foundation of China (Grant No. 51578080). Some reading materials for the book were provided by Prof. Zhigang Zhou, Prof. Hui Wang, Prof. Jusu Li, Ms. Meifang Huang, and Juan Xie of School of Traffic and Transportation Engineering of CSUST. Chun Wang, a postgraduate from School of Foreign Studies of CSUST, translated the book. Ding Yao, Zhenquan Wang, Mengkang Wang, Zhenlin Cheng, Haipeng Deng, and Tanlong Zhang, postgraduates from School of Traffic and Transportation Engineering of CSUST, edited the pictures for the book. We would like to express our sincere gratitude to them.

Changsha, China
November 2017

Jialiang Yao
Zhigang Zhou
Hongzhuan Zhou

About This Book

This book is edited mainly according to research results of composite materials of highway engineering and application experience of practical engineering at School of Traffic and Transportation Engineering of Changsha University of Science & Technology in recent years. Geosynthetics, steel fiber-reinforced concrete, modified asphalt and asphalt mixtures, polymer composite materials, pavement functional layer materials and preventive maintenance materials, engineering properties, selection requirements, and engineering application technology which are widely used in highway engineering are introduced in detail.

It is closely linked with the actual engineering. It can be used as a training textbook and a reference book for technical personnel with foreign projects in engineering. It can also be used as a textbook for postgraduates or a textbook of optional course for undergraduates.

Contents

Chapter 1
Introduction to Composite Materials

1.1 Development of Composite Materials

Composite materials were first used in the 1940s when the glass fiber-reinforced unsaturated polyesters emerged, opening up a new era of modern composite materials [1].

Since the 1960s, a variety of high-performance fibers have developed. Since the 1980s, the development of modern composite materials has reached a higher level because of the rich knowledge and experience in the design, manufacturing, and testing. Various composite materials of matrices have also improved, that is, it has gone into the development stage of high-performance composite materials [2].

The whole process of composite materials can be divided into ancient composite materials, modern composite materials, and advanced composite materials.

A variety of natural composite materials has been used and produced by following nature in ancient time. For example:

Shaanxi Banpo people—they used grass stalks and the mud to build the wall. It has lasted till now;
Lacquerware—it is made from the hemp fiber and the raw lacquer, which has lasted over four thousand years;
Dunhuang frescoes—they were lacquer paints on clay bodies and the surface of palace buildings.

Contemporarily, the development of composite materials began in the 1940s. In the Second World War, the glass fiber-reinforced polyester resin was used by the US Air Force to manufacture aircraft components. In the 1950s, it has rapidly developed [3].

China has begun to develop composite materials since 1958. The modern composite materials have successfully developed since 1942 when the glass fiber-reinforced polyester resin was used by the US Air Force to manufacture components in the Second World War.

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Materials scientists believed that the era of glass fiber-reinforced plastics was from 1940 to 1960, which could be called the first generation of composite materials.

The first generation: glass fiber-reinforced plastics from 1940 to 1960.

The second generation: the development of advanced composite materials from 1960 to 1980; British scientists developed carbon fiber in 1965; American DuPont developed Kevler-49 (Kaifu-49) in 1971. In 1975, the advanced composite materials like carbon fiber-reinforced and Kevler fiber-reinforced epoxy resin have been used on main bearing parts of the aircraft and the rocket. This period was known as the second generation of composite material.

The third generation: the era of the fiber-reinforced metal matrix composite between 1980 and 1990. Among them, the aluminum-based composite is widely used. This period is the third generation of composite materials' development.

It is considered to be the fourth generation of composite materials after 1990 when multifunctional composite materials have mainly developed, such as smart (intelligent) composite and gradient functional composite.

With the continuous emergence of new composite materials, composite materials are not only used in the missile, rocket, satellite, and other cutting-edge industries, but also applied in the aviation, automobile, shipbuilding, construction, electronics, bridges, machinery, medical treatment, and sports.

1.2 Definition and Classification of Composite Materials

1.2.1 Definition of Composite Materials

Broadly speaking, the composite material is a combination of two or more different chemical components. In modern materials, however, composite materials refer to materials consisting of two or more components of different phases. Composite materials are defined as materials with the multiphase, special properties, the three-dimensional combination, and a clear interface between phases which are composed of two or more components with a certain quantity ratio by the choice and artificial complex [3].

According to the definition of composite materials, the characteristics are as follows:

- Components and relative contents of composite materials are artificially selected and designed;
- Composite materials are artificially produced rather than naturally formed (different from natural materials with some composite morphologies);
- The certain components of the composite materials still retain their inherent physical and chemical properties (different from compounds and alloys) after recombination;

- The properties of composite materials depend on the synergistic phase-forming property. Composite materials have new, unique, and available properties that are different or superior to those of single-component material;
- The composite materials are multiphase materials that are distinguished from each other by distinct interfaces.

According to the above definition of composite materials, natural-formed materials with certain composite morphologies, compounds, single-phase alloys, and multiphase alloys should not be included in composite materials.

1.2.2 Structure of Composite Materials

Composite materials consist of two or more components and the interfaces between them. Component materials mainly refer to the reinforcement and the matrix. They are also called the reinforcing phase and the matrix phase. The interface between the reinforcing phase and the matrix phase is also considered as the interface phase of composite materials because of its special structure and component. The reinforced phase is a filament (continuous or chopped), flake or granular with high strength, modulus, hardness, and brittleness, which is the main bearing phase when composite materials are subjected to the external load. They are dispersed in composite materials and are surrounded by the matrix. Therefore, they are also called the dispersed phases. The matrix phase is a coherent material that surrounds the reinforcing phase and is relatively soft and tough. The matrix phase is also called the continuous phase. The matrix phase has the function of supporting and protecting the reinforcing phase. When composite materials are subjected to the external load, the matrix phase acts mainly in the form of shear deformation to enhance the phase distribution and transfer load.

The properties of composite materials depend on the type, properties, content, and distribution of component materials, including the properties of the reinforcement and its surface physical and chemical states, the structure and properties of the matrix, the configuration, distribution, and volume of the reinforcement. Their properties also depend on the production of composite materials, composite methods, and environmental conditions [4].

1.2.3 Classification of Composite Materials

Composite materials can be classified by the shape of the reinforcement and the type of the matrix [5, 6]. According to the shape of reinforcement (agent), they can be divided into three categories: granular, fibrous, and layered. Several typical structures of composite materials were as shown in Fig. 1.1. The asphalt concrete mix is the granular composite material. That is, it is mixed by the appropriate proportion of the

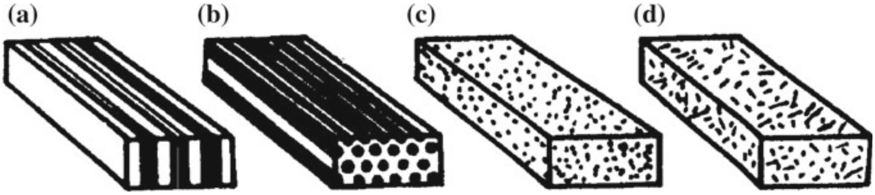

Fig. 1.1 Diagram of structures of composite materials: **a** Laminated composite; **b** Continuous fiber composite; **c** Fine composite; **d** Shortcut fiber composite. Reprinted from Ref. [5], copyright 1997, China Communications Press

coarse aggregate, the fine aggregate, the filler, and the asphalt in the strict control. The fiber-reinforced composite materials are composed of matrices (plastic, resin, rubber, metal, cement, or concrete) and reinforcing agents (glass fiber, carbon fiber or boron fiber, and other ceramic materials). The plywood composed by multilayer woods is one of laminated composite materials.

According to the type of matrix materials, they can also be divided into three categories: resin matrix composite, metal matrix composite, and ceramic matrix composite.

According to the role of composition, they can be classified as follows:

- Functional composite materials: the use of physical, chemical, and biological functions of composite materials as main purposes.
- Structural composite materials: the use of a variety of good mechanical properties of composite materials for the construction or manufacturing structure.

1.2.4 Performance of Composite Materials

The composite materials can concentrate and promote their advantages, and implement the best structural design. Generally, there are following advantages.

1.2.4.1 High Specific Strength and High Specific Modulus

The specific strength is the ratio of the strength to the density. Materials with a higher specific strength can withstand higher stress and have bigger rigidity. The specific modulus is the ratio of the elastic modulus to the density. Composite materials are light and rigid. The specific strength and specific modulus of composite materials are high (if there is a direction, only in a certain direction are the specific strength and specific modulus higher).

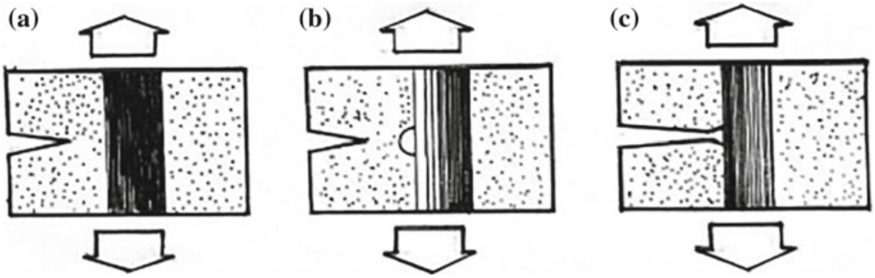

Fig. 1.2 Diagram of fatigue crack propagation of composite materials: **a** Initial crack in the matrix; **b** Crack is blunted near the fiber; **c** Crack propagation in the matrix is blocked by the fiber. Reprinted from Ref. [5], copyright 2015, China Communications Press

1.2.4.2 Good Anti-fatigue Performance

The fatigue performance is the performance of the material under the cyclic stress. The anti-fatigue performance of composite materials is good. First of all, the fibers with small defects have a higher anti-fatigue stress. Second, the plasticity of the matrix can eliminate or reduce the size and quantity of the stress concentration area so that the fatigue source (defects in the fiber and matrix) can form the micro-crack difficultly. Even in the case of micro-crack as shown in Fig. 1.2, the plastic deformation can also make the crack tip blunt and expand slowly. The fatigue strength of the carbon fiber-reinforced resin is 70–80% of the tensile strength, while the general metal material is only 30–50% [5–7].

1.2.4.3 Strong Damping Capacity

The natural frequency of the component is related to the structure and is proportional to the square root of the modulus. The specific modulus of composite materials is large, so its natural frequency is very high. In the case of the general loading speed or frequency, it is not prone to lead to the resonance and the fast brittle fracture. In addition, the composite material is a heterogeneous multiphase system in which there are a large number of (fiber and matrix) interfaces. The interface can reflect and absorb the vibration. The damping of the general matrix is also great. As a result, the attenuation of the vibration in the composite material is very fast. It shows the damping characteristics of the steel and carbon fiber composite materials in Fig. 1.3. The damping rate of the composite material is faster than that of the steel. That is, the time of the composite material when the amplitude is attenuated to zero is shorter than that of the steel [3, 8].

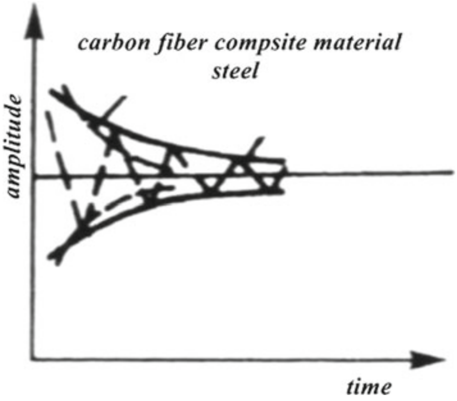

Fig. 1.3 Comparison of damping characteristics of two materials. Reprinted from Ref. [3], copyright 1998, Chongqing University Press

1.2.4.4 Good High-Temperature Performance

The reinforcing fibers have a high modulus of the elasticity so that they often have high melting points and high-temperature strength. The tensile strength of the carbon fiber at high temperature increases, which exceeds the alumina whisker (the whisker refers to acicular short fibers formed by crystal growth with a diameter less than 30 μm and a length of only a few microns). Because of the low melting point of the glass fiber, its high-temperature performance is not better than that of the carbon fiber.

In addition, the thermal stability of composite materials is also good due to the good high-temperature strength, the good fatigue resistance, and the good compatibility with the matrix and the fiber.

1.2.4.5 High Safety Fracture

There are thousands of isolated fine fibers per square centimeter in fiber-reinforced composite materials. They will be a statically indeterminate state when they are stressed. The overloading will make some fibers break, but the stress is quickly reallocated. The rest fiber will bear the load, which does not cause the components to lose the carrying capacity completely and fracture immediately, so the working security is high.

1.3 Reinforcing Theory of Composite Materials

Composite materials are not a simple combination of materials, but a complex process of combining physical, chemical, mechanical, and even biological interactions.

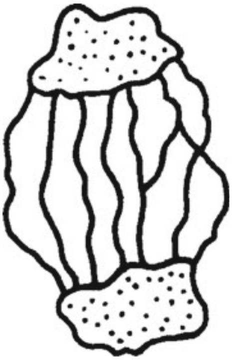

Fig. 1.4 Rubber molecular chain grafted on the surface of carbon black particles. Reprinted from Ref. [5], copyright 1997, China Communications Press

Different composite materials have their own enhanced properties and certain laws. Its characteristics can be summarized as follows.

1.3.1 Reinforcing Mechanism and Mixing Rule of Particle-Modified Composite Materials

1.3.1.1 Reinforcing Mechanism of Particle-Modified Composite Materials

Particle-modified composite materials are divided into particle-modified plastics, particle-modified rubber, particle-modified metal, particle-modified asphalt, particle-modified ceramics, and so on. The particles are highly dispersed in the composite material. For the fine particle-reinforced composite material, the fine particle phase can hinder the movement of the macromolecule chain in the polymer body. There is the crack shielding effect in the ceramic body. In the metal matrix, the particle has the ability to prevent the dislocation. Composite materials are reinforced by the addition of coarse particles in order to obtain a comprehensive performance [5, 9].

The reinforcing mechanism of the particle dispersion of the polymer-based particle composite material is that the active surface of the filler particles is combined with several polymer chains to form a cross-linked structure. When one of the molecular chains is stressed, the stress can be dispersed by the cross-linked point to other molecular chains. If one of the root chains fractures, the other chains can still play a role, which will not endanger the whole. Such as the carbon black-reinforced rubber, the rubber molecular chain may be grafted on the surface of carbon black particles as shown in Fig. 1.4.

The micro-cracking mechanism of ceramic matrix particles composite materials is mainly characterized by the fact that the sintered body produces internal stress during the cooling process. Sometimes, the micro-crack is even produced because the particles do not match the thermal expansion of the matrix or due to the volume expansion caused by the phase change. These stress fields or micro-crack can change the stress field at the front of the main crack in the process of force. The main crack is deflected and bifurcated with the fracture route prolonged, which absorbs more fracture energy, and thus improves the strength of the material.

The metal matrix (dispersion-reinforcing): particles prevent the dislocation with the size of 0.01–0.1 μm. They can bear the part of the load, but the matrix bears the main load. The matrix plays a major role.

According to the size of the particle, the principles of the above particle-reinforcing are divided into two categories: the dispersion-reinforcing mechanism and the particle-reinforcing mechanism.

Dispersion-Reinforcing Mechanism

The dispersion-reinforcing composite materials are composed of the dispersed microparticle and the matrix. The reinforcing mechanism is similar to that of the metal material precipitation. It can be explained by the dislocation theory. The load is mainly borne by the matrix, and the dispersed microparticle hinders the dislocation movement of the matrix. The greater the ability of the microparticle to block the dislocation movement of the matrix is, the greater the reinforcing effect is.

The smaller the microparticle size is and the higher the volume fraction is, the better the reinforcing effect is.

In general, $V_p = 0.01-0.15$, $d_p = 0.001-0.1\,\mu\text{m}$.

Particle-Reinforcing Mechanism

Particle-reinforcing composite material is composed of large size (>1 μm) hard particles and matrices. Its reinforcing mechanism is different from the dispersion-reinforcing mechanism. In the particle-reinforcing composite material, although the load is mainly borne by the matrix, the particles also bear the load and constrain the deformation of the matrix. The greater the ability of the particles to block the dislocation movement of the matrix is, the greater the reinforcing effect is.

The smaller the particle size is and the higher the volume fraction is, the better the reinforcing effect of the particles on the composite material is. Generally, in the particle-reinforced composite material, the particle diameter is 1–50 μm. The particle spacing is 1–25 μm. The particle volume fraction is 0.05–0.5 μm.

1.3.1.2 Rule of Mixture

Suppose x_c as the physical value of the composite material. However, the variations of x_1, x_2, x_3, etc. are the physical values of each component of the composite material. When they are the function of x_c, it can be expressed as follows:

$$x_c = f(x_1, x_2, x_3) \tag{1.1}$$

If v_1, v_2, v_3, etc. are the ratio of the volume of each component to the total volume of the composite material, there is the following relationship of linear combinations:

$$x_c = v_1x_1 + v_2x_2 + v_3x_3 + \cdots \tag{1.2}$$

If the connection interface of particles or fibers and the matrix of the composite material is complete, there is the general rule of mixture.

$$x_c^n = v_1x_1^n + v_2x_2^n + \cdots + v_ix_i^n \tag{1.3}$$

When $n = 1$, the matrix and fiber (particle) are the parallel connection model; when $n = -1$, the matrix and fiber (particle) are the series connection model.

Some properties of composite materials can be predicted by using the rule of mixture. For example, the density of the particulate composite material can be expressed as follows:

$$\rho_c = \sum f_i\rho_i = f_1\rho_1 + f_2\rho_2 + \cdots + f_n\rho_n \tag{1.4}$$

where

ρ_c the density of the composite material;
ρ_i the density of each component of the composite material;
f_i the volume fraction of each component.

But the rule of mixture is not suitable for estimating the hardness and strength of the particle-reinforced composite material.

Example 1.1 The quality mix proportions of various mineral materials of the asphalt mixture are expressed by $(P_1...P_n)$ (%). The relative apparent density of various mineral materials is expressed by $(\gamma_1 \ldots \gamma_n)$. The asphalt content (the percentage of the asphalt mass and the total mass of the asphalt mixture) is expressed by P_b $(\sum P_i + P_b = 100(\%))$. The relative density of the asphalt mixture is expressed by γ_b (25/25 °C). The theoretical density of the asphalt mixture specimen is required for calculating (the compact asphalt mixture specimen is all composed of the mineral and the asphalt). The density reaches the maximum when the porosity is 0. The relative density refers to the density ratio of a certain substance to a reference substance (such as water) under certain specific conditions (the same temperature).

Solution According to the above conditions, the volume percentages of components (mineral and bitumen) can be calculated as follows:

$$f_1 = \frac{P_1/\gamma_1}{P_1/\gamma_1 + \cdots P_n/\gamma_n + P_b/\gamma_b}$$

$$f_n = \frac{P_n/\gamma_n}{P_1/\gamma_1 + \cdots P_n/\gamma_n + P_b/\gamma_b}$$

$$f_b = \frac{P_b/\gamma_b}{P_1/\gamma_1 + \cdots P_n/\gamma_n + P_b/\gamma_b}$$

The density of the asphalt mixture relative to water according to the rule of mixture is calculated as follows:

$$\rho_t = \sum f_i \rho_i = \frac{100}{P_1/\gamma_1 + \cdots + P_n/\gamma_n + P_b/\gamma_b}$$

The theoretical density of the asphalt mixture is calculated as follows:

$$\rho_t = \rho_t \rho_w = \frac{100}{P_1/\gamma_1 + \cdots + P_n/\gamma_n + P_b/\gamma_b} \rho_w$$

1.3.1.3 Influencing Factors of Properties of Particle-Modified Composite Material and Its Applications

- The particle volume fraction (with a certain range);
  Example: The clay filled with the polyethylene space can reduce costs and improve stiffness.
- The distribution of uniformity;
- The particle diameter and the diameter ratio of two particles.

When the particle diameter is from 100 to 2500 angstroms, the particles play a role of the dispersion-reinforcing effect because it can prevent the dislocation movement. This type of particle is also called the dispersant. It is required to be hard, stable, and insoluble with the matrix. In addition, the matrix has a good binding force. It is applied less in the current civil engineering.

Particles those are more than 2500 angstroms are to improve the comprehensive performance. There is mainly polymer modification (calcium plastic material) and asphalt modification in the application of civil engineering materials. For example, the strength, stiffness, and thermal stability of asphalt can be improved when the SBS powder-modified asphalt and the carbon black (50 Egypt–5000 Å)-modified asphalt are added.

The relationship between the reinforced particle and the matrix particle size is different from different systems. For example, fine particles of SiC–TiC have good toughening performance while coarse particles of SiC–Si_3N_4 are better, which results from different toughening mechanisms.

- The properties of particles, particles and the chemical compatibility of matrix, the stability, and so on.

1.3.2 Reinforcing Mechanism of One-Way Arrangement of Continuous Fiber-Reinforced Composite Material

1.3.2.1 Fiber-Reinforcing Reasons

- The micro-crack hypothesis: the theoretical strength of the glass depends on the gravitational force between molecules or atoms. The theoretical strength is high, which can reach 2000–12,000 MPa. But the theoretical toughness of the glass is much higher than the actual strength. It is because of the micro-cracks with different amounts and sizes in the glass or glass fiber, which thus reduces the strength greatly.
- The critical crack size (the necessary size for rapid expansion of the crack) increases relatively with the decreasing diameter of the fiber itself.
- It is hard to damage the crack by the matrix protection.
- In the state of the uneven three-way stress, the fiber brittleness decreases.

1.3.2.2 Reinforcing Mechanism of Unidirectional Continuous Fiber-Reinforced Composite Materials

The properties of composite materials are related to the properties of components, the distribution of components, and the physical and chemical interactions between components. The properties of composite materials can be determined experimentally. The longitudinal properties of some unidirectional composite materials can also be analyzed by mathematical models.

The single layer in the unidirectional fiber-reinforced composite material is shown in Fig. 1.5. The longitudinal axis is parallel to the fiber direction. The transverse axis is perpendicular to the fiber direction [1, 10, 11].

Mixing Rate Law of Longitudinal Strength and Stiffness

Stress of Composite Material—Initial Period of Strain Curve

The laminates of continuous fiber-reinforced composite materials are subjected to the tensile stress in the fiber direction, assuming that the fiber properties and diameters are uniform, continuous, and all parallel to each other. The combination between the fibers and matrix is perfect, and there is no relative slip at the interface. The thermal expansion coefficient between the fiber and the matrix, Poisson's ratio, and the additional stress caused by the elastic deformation are ignored. The longitudinal strain of the entire material can be considered to be the same. That is, the composite material, the fiber, and the matrix have the same strain.

$$\varepsilon_c = \varepsilon_f = \varepsilon_m \tag{1.5}$$

Considering that the external load in the fiber direction is shared by the fiber and the matrix, it should be expressed as follows:

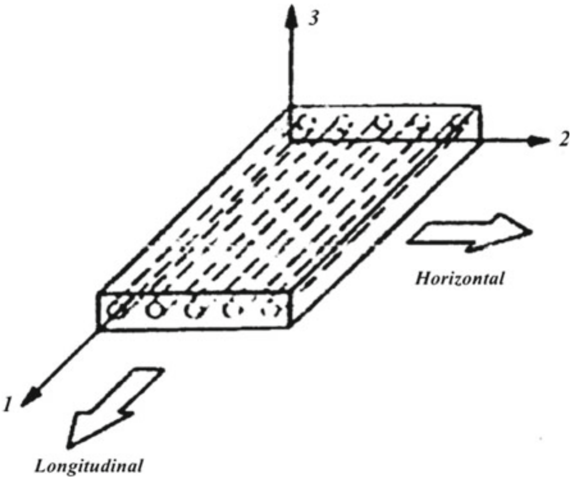

Fig. 1.5 Single-layer plate in the unidirectional composite material. Reprinted from Ref. [1], copyright 2003, Shanxi Science and Technology Press

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m \tag{1.6}$$

A represents the cross-sectional area of the corresponding component in the composite material. The above formula can be converted as follows:

$$\sigma_c = \sigma_f A_f / A_c + \sigma_m A_m / A_c \tag{1.7}$$

For the parallel fiber-reinforced composite material, the volume fraction is equal to the area fraction.

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \tag{1.8}$$

The strain of the composite material, the fiber, the matrix is the same. The derivative of the strain is calculated as follows:

$$\frac{\mathrm{d}\sigma_c}{\mathrm{d}\varepsilon} = \frac{\mathrm{d}\sigma_f}{\mathrm{d}\varepsilon} V_f + \frac{\mathrm{d}\sigma_m}{\mathrm{d}\varepsilon} V_m \tag{1.9}$$

$\mathrm{d}\sigma/\mathrm{d}\varepsilon$ represents the slope of the corresponding stress–strain curve at a given strain. If the stress–strain curve of the material is linear, the slope is a constant. It can be substituted by the corresponding elastic modulus as follows:

$$E_c = E_f V_f + E_m V_m \tag{1.10}$$

The above three formulas show that the contribution of the fiber and the matrix to the average performance of the composite material is proportional to their respective volume fraction, which is consistent with the rule of mixture.

In the case where both the fiber and the matrix are linearly elastic, the stress and the load of the fiber and the matrix are deduced as follows:

$$\frac{\sigma_c}{E_c} = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m} \tag{1.11}$$

So there is following formula:

$$\frac{\sigma_f}{\sigma_m} = \frac{E_f}{E_m} \cdots \frac{\sigma_f}{\sigma_c} = \frac{E_f}{E_c} \tag{1.12}$$

It can be seen that the stress ratio of each component in the composite material is equal to the corresponding elastic modulus ratio. In order to effectively utilize the high strength of the fiber, the fiber should have a much higher elastic modulus than that of the matrix. The component-bearing ratio in the composite material can be expressed as follows:

$$\frac{P_f}{P_m} = \frac{\sigma_f A_f}{\sigma_m A_m} = \frac{V_f E_f}{V_m E_m} \tag{1.13}$$

$$\frac{P_f}{P_c} = \frac{\sigma_f A_f}{\sigma_f A_f + \sigma_m A_m} = \frac{\frac{E_f}{E_m}}{\frac{E_f}{E_m} + \frac{V_m}{V_f}} \tag{1.14}$$

The higher the elastic modulus ratio of the fiber and the matrix is, the higher the fiber volume content is and the greater the fiber-bearing is. Therefore, for a given fiber, the matrix system should increase the volume fraction of the fiber as much as possible. However, when the volume fraction is too high, the impregnation and wetting degree of the fiber decreases, which results in the decrease of the interface bonding of the fiber and the matrix and the increase of the porosity. The composite material performance is rather worse.

Behavior of Composite Material after Initial Deformation

Generally, the deformation of composite material has four stages: (1) both the fiber and the matrix are linearly elastic deformation; (2) the fiber continues to be linearly elastic deformation and the matrix is nonlinearly deformation; (3) both the fiber and the matrix are nonlinearly deformation; and (4) The composite material breaks as the fiber breaks. For composite material with large ductility, the second period may account for a significant portion of the stress–strain curve of composite material due to the plastic deformation of the matrix. The elastic modulus of composite material can be calculated as follows:

$$E_c = E_f V_f + \left(\frac{\mathrm{d}\sigma_m}{\mathrm{d}\varepsilon}\right)\varepsilon_c V_m \tag{1.15}$$

where $d\sigma_m/d\varepsilon$ is the slope of matrix stress–strain curve of corresponding composite material strain point ε_c. Generally, brittle fiber composite material comes into the third stage.

Fiber Spacing Theory
In 1963, it was distributed by J.P. Romualdi and J.B. Basten.

The basic idea of this theory is that there are different scales and shapes of pores, defects, and micro-cracks in the matrix. When the external force is applied, the stress concentration at these sites causes the fracture to expand, leading to the premature destruction of the structure. Therefore, the tensile strength of the cracked material must be as small as possible to reduce the scale and quantity of the fractured source, mitigate the stress concentration at the tip of the crack, and improve the ability to inhibit the extension and development of the fracture.

$$\sigma = \frac{Kc}{B\sqrt{\overline{S}}} \tag{1.16}$$

Kc the fracture toughness: the crack resistance. It is related to the properties of the material;
$\overline{S}$ Average fiber spacing
B constant
σ is inversely proportional to $\sqrt{\overline{S}}$. That is, the smaller the average fiber spacing is, the higher the initial crack strength is.

There is a critical value on the fiber-reinforcing effect. When the actual fiber content is greater than this critical value, there is a significant reinforcing effect. Below this value, the reinforcing is not significant, or even reduces the matrix strength. The critical value is expressed by the volume ratio.

1.3.2.3 Influencing Factors of Properties of Fiber-Reinforced Composite Materials

Ratio of Length to Width of Fiber
When the ratio of l/d is greater, the enforced effect is better. But the short fiber is easy to mix in the construction. There is a minimum length in the short fiber.

- The smaller d is, the smaller the surface area is. There is a corresponding reduction in brittle fracture caused by the surface defects.
- The end bearing capacity is small.
- The concentration of the end stress is easy to cause cracks.

The volume percentage of the fiber: a minimum and a maximum (80%), depends on the ability of the matrix material to surround the fiber.

The minimum volume ratio of the fiber can also be called the critical volume ratio: V_{fcr}.

Definition When the matrix cracks, the fiber can bear the load caused by the unloading of the matrix. It cannot use the minimum volume ratio of the fiber when the bearing capacity of the composite material decreases.

When $V_f < V_{\text{fcr}}$, the matrix once cracks, the fiber immediately pulls out or pulls off. The composite material is brittle and its strength is controlled by the matrix.

When $V_f > V_{\text{fcr}}$, the transferring load caused by the matrix cleavage does not cause the fiber to pull off or pulled out immediately but can bear a greater load. The strength and the damage form of the composite material are controlled by the fiber.

When the matrix is about to crack, the strain reaches the limit: $\varepsilon_\mu = \varepsilon_f = \varepsilon_c$.

$$\sigma_c = \varepsilon_\mu E_f V_{\text{fcr}} + \sigma_\mu (1 - V_{\text{fcr}}) \tag{1.17}$$

(Assuming continuous parallel)

After cracking of the matrix,

$\sigma_m = \sigma_\mu = 0$,$\sigma_c$ is borne by the fiber alone and reaches σ_{fu}

$$\sigma_c = V_{\text{fcr}} \sigma_{fu} \tag{1.18}$$

$$\begin{aligned} &\because \sigma_c = \varepsilon_\mu E_f V_{\text{fcr}} + \sigma_\mu (1 - V_{\text{fcr}}) \\ &\therefore V_{\text{fcr}} = \frac{\sigma_\mu}{\sigma_{fu} - \varepsilon_\mu E_f + \sigma_\mu} \end{aligned} \tag{1.19}$$

Fiber Orientation

It is basically isotropic in the random arrangement but the mechanical performance is not the best one-dimensional direction of the arrangement. The material is anisotropic. The parallel direction is better than the vertical direction.

Fiber Performance

The fiber should have high strength, lightweight, high toughness, and high melting.

Matrix Performance

It is related to the chemical compatibility with the fiber, the compatibility of the manufacturing process, and the stability of the environment.

For example, when the steel fiber is in the cement matrix, the cement can protect the steel fiber. The effect of the matrix on the composite material is mainly shown in the interlayer shear, as well as the compression resistance and the bending resistance.

Fabric fibers in the cement matrix will be alkaline erosion.

Interface Strength between the Fiber and the Matrix

It should not be too low and too high. It is too high to result in the brittle fracture. Measures are as follows: ① to roughen the fiber surface; ② to coat the coupling agent; and ③ to form the surface-active groups.

1.4 Hydrothermal Effect of Composite Materials

When the material is heated, the volume will expand. When the temperature decreases, the volume will shrink. At this time, the tensile or compressive thermal strain will be produced in the material. If the material is subject to constraints or uneven heating or cooling, the tensile or compressive thermal strain will be also produced in the material. Sometimes, the bending strain stress will be produced. For some materials, when they absorb water, the volume will expand. When they lose water, it will shrink. In the composite material, these two cases occur, which is the so-called hydrothermal effect.

1.5 Compatibility and Wettability of Matrix and Reinforcement

1.5.1 Compatibility

The compatibility of the matrix and the reinforcement refers to the performance of the long-term stability in the manufacture and the use of composite materials. There is the physical compatibility and the chemical compatibility.

1.5.1.1 Physical Compatibility

The physical compatibility refers to the degree in which the components cooperate with each other under the change of the stress and the temperature of composite materials. The former is the problem of the mechanical compatibility while the latter is the problem of the thermal compatibility.

1.5.1.2 Chemical Compatibility

The chemical compatibility mainly refers to whether there is the chemical reaction or not between the components of composite materials and what the reaction speed is. It includes both the thermodynamic compatibility and the kinetic compatibility.

1.5.2 Wettability

The molecular state of the surface layer is different from the internal molecular state. The molecule energy of the surface layer is higher than that of the internal molecule. When the solid material contacts the liquid material, it will reduce the adsorption phenomenon of the surface energy with the formation of the interface. The liquid will spread over the surface of the solid matter. This phenomenon is called the wetting. The ability of the liquid to spread over the solid surface is called the wettability. The wettability of the liquid can be expressed by the contact angle θ.

The following measures can be taken to improve the wettability of the matrix and the reinforcing agent.

To Change the Surface State and Chemical Component of Solid Reinforcing Agent

The main method is to treat the surface of the reinforcing agent, including the physical and chemical cleaning, the mechanical and electrochemical polishing, the corrosion, the coating, etc. For the particle-reinforced composite materials, the surface treatment is mainly to remove the gas and water on the surface of particles, which can be used by the high-temperature heating, the vacuum baking, the ultrasonic oscillation, the surface coating, etc. In recent years, some people have used the laser treatment to make the SiC surface modify and promote the wetting.

To Change the Chemical Component of Liquid Matrix

Adding elements to the matrix can alter the chemical component of the matrix and promote the wetting. For example, in the *Al–C* system, adding elements to the aluminum matrix that strongly reacts with carbon can produce the carbide elements (such as Ti, Ta, N, Zr, Hf, etc.) and improve the wettability of the aluminum to the carbon fibers.

To Change the Temperature

Usually, the increasing temperature can reduce the contact angle between the liquid matrix and the solid-reinforced agent, and improve the wettability. If the temperature is less than 1000 °C, the aluminum cannot wet the graphite. If the temperature is higher than 1000 °C, the contact angle can be less than 90°.

To Improve the Liquid Pressure

The liquid matrix cannot spontaneously penetrate the fiber bundle unless under a certain external pressure.

1.6 Interface of Composite Material

In general, the interface of the composite material is produced in the manufacturing process of the composite material, when the composite material is composed of the reinforced material and the matrix of the different chemical components. Through the contact, some elements are diffused and dissolved so that the chemical reaction generates a new phase, which is called the interface phase.

1.6.1 Definition of Interface of Composite Material

The interface between the reinforcement and the matrix in the composite material is a new phase–interface phase. Its structure varies from the matrix and reinforcement with a certain thickness (> nm) and has obvious difference from them. The interface phase can be the reaction product layer of the matrix and the reinforcement in the manufacture and the use of the composite material. It can also be a diffusion bonding layer or a component transition layer or a residual stress layer formed by the different physical properties between the matrix and the reinforcement. It can even be a man-made coating for controlling the interface properties of the composite material, or a gap between the matrix and the reinforcement [5, 6].

1.6.2 Role of Interface Phase

The interface phase is a part of the composite material and its functions are as follows:

- The transferring function: The interface can transmit force. That is, the external force transmitted to the reinforcement plays a role of the bridge for the matrix and the reinforcement.
- The blocking function: To combine with the appropriate interface can prevent the crack propagation, interrupt the material damage, and slow down the role of stress concentration.
- The protecting function: The interface phase prevents the reinforcement from the environmental erosion and prevents the matrix and the reinforcement from the chemical reaction, which plays a role of protecting the reinforcement.

1.7 Composition Effect

The components A and B are combined to obtain a comprehensive effect which has both the performance of component A and the performance of component B, which is called the composition effect. After the composition of different components, there may be two kinds of composition effects: the linear effect and the nonlinear effect. Linear composition effect includes the mean effect, the parallel effect, the complement effect, and the offsetting effect. The nonlinear composition effect includes the multiplication effect, the induction effect, the system effect, and the resonance effect.

1.8 Design Content and Method of Composite Materials

1.8.1 Design Content of Composite Materials

The composite material design includes the selection of the unit components, the selection of the composite manufacturing process, and the estimation of the composition effect [7, 12, 13].

1.8.1.1 Selection of Unit Component Material

The problems in selecting unit components must be noted as follows.

The compatibility between the components (including physical, chemical, and mechanical compatibility), such as whether the coefficient of thermal expansion matches between the components, whether the harmful reaction is produced between the components in the manufacturing and service and whether the strain of each component and the composite material is coordinated with each other when the composite material bears the load.

The geometrical shape of the reinforced component (the granular shape, stripe shape, fibrous shape and their knitting and stacking shapes, etc.) is determined by the functions of each component and their position and orientation in the composite material.

In the preparation of composite materials, each component should maintain its inherent excellent nature and can avoid the weaknesses and complement each other to produce the required composition effect.

According to the design goals of composite materials, the following basic requirements should be met in the selection of the composite material.

Requirements for the fiber are as follows: the high strength, the high modulus, the easy production and processing, the good chemical stability, the mechanical damage resistance, the appropriate size and geometry, the good fiber reproducibility (or consistency), the good toughness, and the proper price for the user.

The requirements for the matrix are as follows: the strong environment resistance, the density as low as possible, the good filling of the reinforcement, the high cohesive strength, the high fracture toughness, the good connection with the reinforcement, the high-temperature oxidation resistance, and the good shape.

1.8.1.2 Preparation Method

After the design of material component, it is necessary to consider the composite process route, that is, the specific preparation method.

The following four aspects should be mainly considered in the selection of preparation method:

The selected process method must do minimal damage to the material components. Especially when fiber or whisker is incorporated into the matrix, some mechanical mixing methods often result in the damage of fiber or whisker.

It enables any form of reinforcing material (fibers, granules, whiskers) to be uniformly distributed or lined according to predesigned requirements.

It makes the finally formed composite material to fully play roles of various components on the performance, that is, to avoid weakness. Each component still retains its inherent characteristics.

The performance–price ratio should also be considered in the selection of preparation method. If requirements of the use of composite materials can be met, it is as far as possible to select simple and easy process to reduce preparation cost.

1.8.2 Design Method of Composite Materials

Corresponding to different design goals, there are five design methods: the safety design, the single performance design, the design of equal bearing capacity, the isostiffness design, and the optimal design.

The safety design: the safe work of the designed structure or component is required in use. The specific performance indicators are required to meet (such as strength, modulus, etc.).

The single performance design: a certain performance of the composite material is required to meet such as the filter, the drainage, the zero expansion, the high-temperature resistance, or the chemical medium resistance. But the designer must consider other requirements of the performance as much as possible once the main requirements are met.

The design of equal bearing capacity: the anisotropy is required to meet the work and the direction required by the environment for materials.

The isostiffness design: the stiffness is required to meet the restricted condition for the deformation and there is no excessive redundancy.

The optimal design: even if the objective function takes the extreme value design, the objective function can be various. Therefore, different objective functions have different optimal objects such as the minimum quality, the maximum life, the lowest cost, the lowest fees in a unit time, and so on.

1.9 Commonly Used Composite Materials in Highway Engineering

With the development of highway and bridge construction technology, the composite materials used for highway and bridge construction are increasing in variety, and new requirements are constantly put forward for their quality. Commonly used composite materials in highway engineering are introduced as follows.

Geosynthetics

Geosynthetics is the general term of composite materials in the civil engineering. As a new type of civil engineering materials, synthetic polymers such as plastics, chemical fibers, and synthetic rubbers are used as raw materials to manufacture various types of geosynthetics. It is placed in the soil, on the surface or among various soils to strengthen or protect the soil. It is commonly used for filtration, drainage, isolation, reinforcement, seepage prevention, and protection in highway engineering.

Steel Fiber-Reinforced Concrete

Steel Fiber-Reinforced Concrete (SFRC) is a composite material that the steel fiber is evenly mixed with ordinary concrete. Due to the good mechanical property of steel fiber-reinforced concrete, it is mainly used as structural composite materials in highway engineering. It is commonly used in concrete pavement, bridge deck pavement, slope protection engineering, and tunnel lining.

Modified Asphalt and SMA

The modified asphalt including modified asphalt mixture is made from addictives (modifiers), such as rubber, resin, polymer, rubber powder, or other fillers, or taking some measures, such as taking mild oxidation of asphalt to improve the properties of asphalt.

Stone Mastic Asphalt (SMA) is a kind of asphalt mixture with dose skeleton structure which is composed of coarse aggregate, mineral powder, asphalt, and intermediate size particles.

Modified asphalt and SMA are commonly used in important asphalt pavement (bridge deck) or asphalt pavement in extreme weather conditions.

Polymer Matrix Composites

Polymer matrix composites consist of polymer matrix or polymer reinforcement. They are mainly used in road maintenance, bridge reinforcement, and corrosion prevention of highway concrete structure.

Functional Layer Materials and Preventive Maintenance Materials of Pavement

The functional layer of pavement is regarded as an unstructured layer in the mechanics model of pavement. The preventive maintenance of pavement is a planned cost-effective conservation strategy for existing road system without structural damage under the condition of functional deficiency.

The functional layer materials (slurry seal, micro-surfacing, isolation materials, etc.) and the preventive maintenance materials (wax curing agent, joint sealing materials, ultrathin wearing course materials, etc.) of pavement are commonly used in highway engineering.

Exercises

1. What role does the reinforcement, the matrix, and the interface play in the composite material?
2. What performance do composite materials have?
3. What is the prerequisite (or basic assumption) of applying the rule of mixture to calculate the performance of fiber composite materials?
4. Contrast the role and the mechanism of the particle reinforcement and the fiber reinforcement.
5. What aspect should be considered to improve the interface boning?
6. It is assumed that the thermosetting polyester is filled with hollow glass balls. The outer diameter of the glass balls is 1 mm. The wall thickness is 0.01 mm. The glass density is 2.5 g/cm^3. The polyester density is 1.28 g/cm^3. If the density of the composite material is 0.85 g/cm^3, calculate the number of glass microspheres required per cubic meter.
7. The polyester carbon fiber contains 30% high-strength carbon fiber (volume). If the polyethylene fiber is used to achieve the same elastic modulus, calculate (a) the required volume percentage of the polyethylene fiber; (b) contrast the specific modulus of the polyester carbon fiber and the polyethylene fiber. The density of the polyester is 1.28 g/ cm^3, and the modulus is 4.55 GPa. The density of the carbon fiber is 1.78 g/ cm^3, and the modulus is 2.0 GPa. The density of the polyethylene fiber is 0.97 g/ cm^3, and the modulus is 1.17 GPa.

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Chapter 2
Geosynthetics

2.1 Classification and Characteristics of Geosynthetics

2.1.1 Types of Geosynthetics

There is no uniform guideline for the classification of geosynthetics. It was divided into the geotextile, the geomembrane, the special geosynthetics, the composite geosynthetics, and others in *Geosynthetics application of technical specifications* (GB50290-98) [1]. The special geosynthetics includes the geogrid, the geonet, the geomat, the geocell, the geoplastics, and so on. The composite geosynthetics is made from the abovementioned materials, such as the composite geomembrane and geosynthetic composite drainage materials [2].

2.1.1.1 Geotextile

The geotextile is permeable. In general, the geotextile is manufactured by two steps. First, the polymers are processed into silks, short fibers, yarns, or strips. The geotextile of the flat structure is then manufactured. According to the manufacturing methods, it is divided into the knitted geotextile, the nonwoven geotextile, and the woven geotextile. The knitted geotextile is rarely used currently. 80% geotextiles in the world are nonwoven geotextiles.

The main advantages of geotextiles are as follows: the lightweight, the good continuity (it can be made as an entirety with a large area), the convenient construction, the high tensile strength, the corrosion resistance, and the microbial erosion resistance. The disadvantage is that the anti-ultraviolet ability is low without the special treatment.

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2.1.1.2 Geomembrane

The geomembrane is generally divided into the asphalt and the polymer (synthetic polymer). The asphalt geomembrane is mainly used for the composite geotextile (including the woven or nonwoven geotextile) as an infiltration binder. The polymer geomembrane is divided into the plastic geomembrane, the elastic geomembrane, and the combined geomembrane according to different main materials. The geomembrane has outstanding anti-seepage and waterproof performances.

2.1.1.3 Special Geosynthetics

Geogrid

The geogrid is a major geosynthetics. Compared with other geosynthetics, it has a unique performance and efficacy. It is often used as the reinforced material of the reinforced fill structure or geosynthetics. It is widely used for the reinforced roadbed road in domestic and foreign projects. It is divided into the plastic geogrid and the glass fiber geogrid.

Geomembrane Bag

The geomembrane bag is a continuous (or separate) bag-like material. It is made of a double-layer polymeric chemical fiber fabric. It can replace the template and use a high-pressure pump to pour the concrete or mortar into the film bag. The plate or other shape structure is finally formed. It is used for the slope protection or other foundation treatment works.

Geonet

The geonet is braided by the synthetic material strip and the coarse strand or pressed by the synthetic resin with large holes, the large stiffness plat structure, or the three-dimensional structure. It is used for the soft foundation-reinforced cushion, the slope protection, the planting grass, and the manufacture of materials combined with geosynthetics.

Geomat and Geocell

Both the geomat and the geocell are special three-dimensional structure of synthetic materials. The former is mostly three-dimensional permeable polymer mesh mat which is made of filaments. The latter is honeycomb or grid-like three-dimensional structure which is made of the geotextile, the geogrid, or the geomembrane and the strip polymer. It is commonly used for the anti-erosion and the soil conservation engineering. Those have high stiffness and high confined capacity are used for the ground-reinforced cushion or the support structure.

Composite Geosynthetics

Two or more materials such as the geotextile, the geomembrane, and some special geosynthetics are combined with each other and become the composite geosynthetics. The composite geosynthetics can combine the properties of different constituent materials to meet the needs of specific engineering well and have many functions.

2.1.2 Characteristics of Geosynthetics

Characteristics of geosynthetics include lightweight, high strength, good elasticity, abrasion resistance, acid and alkali resistance, uneasily perishable and moth-eaten, low hygroscopicity, and so on. However, it is easy to be aging with sunlight. Therefore, it should not be exposed to the sun for long time in the construction and application.

2.2 Engineering Characteristics of Geosynthetics

2.2.1 Physical Characteristics

2.2.1.1 Thickness

The thickness of geosynthetics is expressed in mm. The thickness variation has a great influence on the hydrodynamic characteristics such as the porosity, the water permeability, and the filterability of the fabric. The thickness of geomaterials in the pressure changes a lot. It is required to determine the thickness at a fixed pressure. The pressure is generally set at 2 kPa. The 25 cm^2 pressure area is generally required. The sample area should be 2 times more than the pressure area. The pressure time is 30 s, and the sample is not less than 10 pieces [3, 4].

2.2.1.2 Unit Area Mass

The mass per unit area is the mass of geosynthetics per unit area. It reflects various properties of materials such as the tensile strength, the breaking strength, the porosity and the permeability, and other mechanical properties. It is one of the main physical properties of geosynthetics and usually expressed by g/m^2.

It is measured by the weighing. The sample area is 100 cm^2, and the sample is not less than 10 pieces. The scale reading should be accurate to 0.01 g (0.1 g for the spot test). Before the test, the constant temperature (20 ± 2 °C) and constant humidity (65 ± 2%) for 24 h are required for the sample in the standard atmospheric pressure.

2.2.2 Mechanical Characteristics

The main indices which reflect mechanical characteristics of geosynthetics include the tensile characteristic and strength, the tearing strength, the bursting strength, the puncturing strength, the penetrating strength, the gripping strength, etc.

2.2.2.1 Tensile Characteristic and Strength

Geosynthetics is flexible. It plays a role in engineering mostly through its tensile strength to withstand the load. Therefore, the tensile strength and its strain are the main characteristics of geosynthetics.

There are some changes of the geotextile thickness during the process of stress. It is not easy to accurately determine. So the stress is generally expressed by kN/m or N/m rather than the stress per unit area.

At present, the tensile strength is basically followed by the tensile test method of the textile strip. That is, the specimen is clamped at both ends with a clamp and the load is applied for stretching at a certain rate until it is damaged. The tensile strength and the deformation of the specimen are measured and the stress–strain curve is drawn. The tensile strength of each sample can be directly read by the tension machine or measured from the record curve, and then calculated by the following formula:

$$T_s = P_f / B \tag{2.1}$$

where T_s is the tensile strength (kN/m); P_f is the maximum tensile strength (N, kN) for reading; B is the sample width (m).

The elongation is calculated as follows:

$$\varepsilon_p = \frac{L_f - L_0}{L_0} \tag{2.2}$$

where ε_{p} is the elongation. L_0 is the initial length (mm) of the sample. L_f is the length (mm) of the sample corresponding to the maximum tension.

At present, the tensile mechanical characteristics of geosynthetics are generally tested by using the indoor unconfined tensile test. However, the mechanical characteristics of the site steel buried in the filler are greatly different due to the binding effect of the filler.

Factors such as the densification of filler materials and the embedding effect of particles should be considered in the experiment [3, 4].

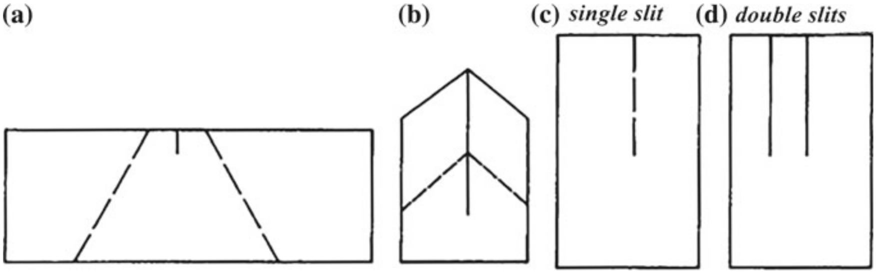

Fig. 2.1 Specimen shape of tearing test: **a** Trapezoid method; **b** Wing method; **c** Single slit; **d** Double slits. Reprinted from Ref. [5], copyright 2001, China Communications Press

2.2.2.2 Gripping Strength

The phenomenon that geotextiles bear the concentration is widespread. The gripping strength reflects its ability to disperse the concentration. The instrument of the gripping strength test is generally the same as the strip tensile test but the test method is different. The gripping strength test is a tensile test that holds the width of both ends of the specimen. Its strength consists of two parts: the tensile strength of the specimen being held by the gripping width and the additional tensile strength provided by the adjacent fibers.

2.2.2.3 Tearing Strength

Geotextiles and geomembranes often have different degrees of damage in the laying and using process. The tearing strength reflects the ability of the specimen to resist the expansion of the breakage gap. It is an important mechanical index to evaluate the breakage expansion of the different geotextiles and geomembranes in the application of geosynthetics.

The tearing strength test is shown in Fig. 2.1. At present, the trapezoid tearing method is used to determine the tearing strength of geomembrane and geotextile. This test is similar to the tensile test from the augmentation way.

The trapezoid tearing strength values of the geotextile are generally 0.15–30 kN. The trapezoid tearing strength values of the non-reinforced geomembrane are generally 0.03–0.4 kN [5, 6].

2.2.2.4 Bursting Strength, Puncturing Strength, and Penetrating Strength

Geotextiles and geomembranes are often placed between two different sizes of materials and affected by the bursting effect of granular materials in the engineering application. The construction will also be affected by the normal stress caused by

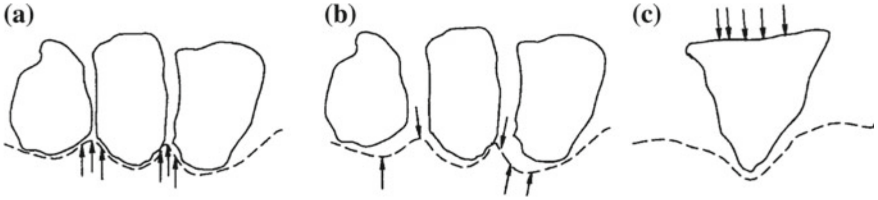

Fig. 2.2 Possible stress states of geotextiles during the filling: **a** Bursting strength; **b** Puncturing strength; **c** Penetrating strength. Reprinted from Ref. [5], copyright 2001, China Communications Press

dumping granular materials. According to the particle size, the stress feature and the damage form of the geotextile and geomembrane can be divided into the bursting strength, the puncturing strength, and the penetrating strength (Fig. 2.2).

The bursting strength is the ability of reflecting the normal pressure of the geotextile and geomembrane against the plane of the vertical fabric. Compared with the penetrating strength test, the pressure area of the bursting strength test is relatively large and the material is bidirectional. The test methods include hydraulic bursting test (Fig. 2.3a), ball-bursting test (Fig. 2.3b), and CBR bursting test (Fig. 2.3c).

The penetrating strength is to reflect the ability of the geotextile or geomembrane to resist small areas of the concentrated load (such as angular stones or branches, etc.). The test method is similar to the ball-bursting test, except that the metal rod is used to replace the ball, as shown in Fig. 2.4.

The penetrating strength is measured by the penetrating test. This test is to simulate the construction of sharp stones or other sharp objects that fall on the geotextile or the geomembrane. The hole size in the penetration test is to assess the ability of the geotextile or the geomembrane to resist the penetration, as shown in Fig. 2.5.

2.2.2.5 Creep Characteristic

The creep of the material is the phenomenon that the deformation of the material increases with time under the constant stress of the material. The creep characteristic is one of the important characteristics of geosynthetics. It is the key to the long-term use [7].

There is no uniform standard for the creep characteristic test. The wide sample (200 mm width) is generally used, and the suspension of metal hammer is used for the load. The applied load is divided into several stages, such as the bursting strength of 25, 50, and 75. During the test, the strain amount at different times is recorded and the half-logarithmic curve of the strain and the time logarithm under different loads is drawn, as shown in Fig. 2.6.

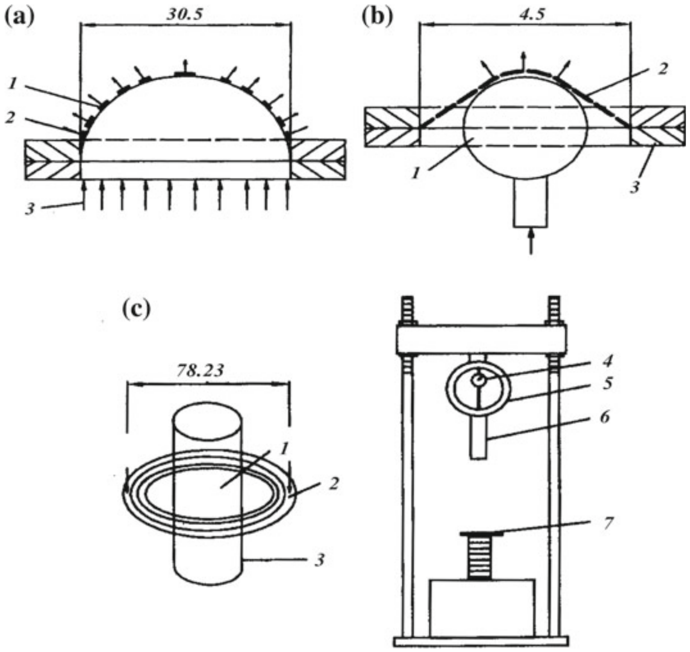

Fig. 2.3 **Bursting test method**: **a** Hydraulic bursting test (unit: cm), 1—Geotextile; 2—Rubber film; 3—Hydraulic; **b** Ball-bursting test (unit: cm), 1—Ball; 2—Geotextile; 3—Ring fixture; **c** CBR bursting test (unit: cm), 1—Fabric; 2—Fixture; 3—Ejector pins of φ50 mm; 4—Percent meter; 5—Proving ring; 6—Cylindrical ejector pins; 7—Pallet. Reprinted from Ref. [5], copyright 2001, China Communications Press

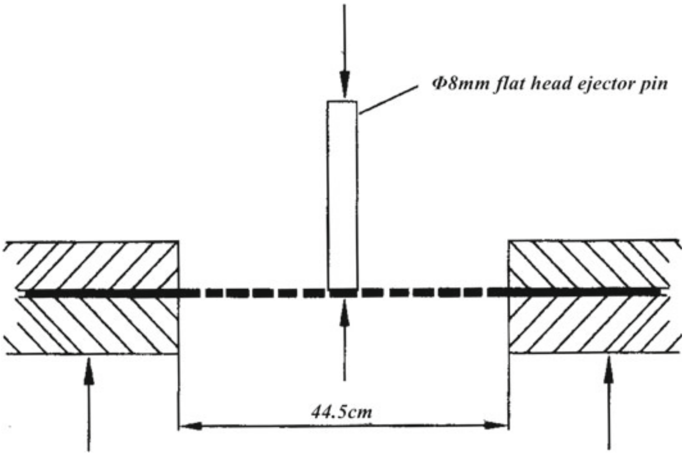

Fig. 2.4 Penetrating test. Reprinted from Ref. [5], copyright 2001, China Communications Press

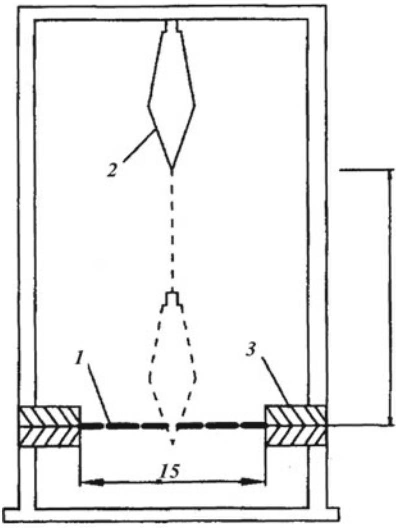

Fig. 2.5 Penetrating test. Reprinted from Ref. [5], copyright 2001, China Communications Press

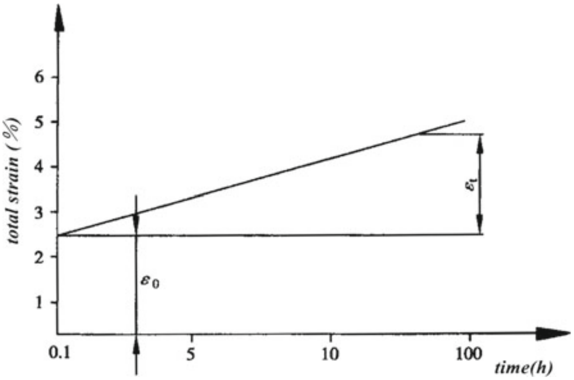

Fig. 2.6 Strain–time logarithmic relationship. Reprinted from ref. [5], copyright 2001, China Communications Press

2.2.3 Interfacial Friction Characteristic of Geosynthetics and Soil Interaction

Geosynthetics as a reinforced material buried in the soil, or as a filter layer on the slope will form a complex system with the surrounding soil. When two materials are deformed under the external load and the self-weight, they will interact along their interfaces. In the realistic project, the geotextile-reinforced material in the filler may appear two kinds of stress states: the direct shear or the drawing.

The interfacial friction characteristic of geosynthetics and the soil is measured by the direct shear instrument which is generally similar to that of the conventional geotest. The site conditions are often simulated in the drawing test, and a variety of

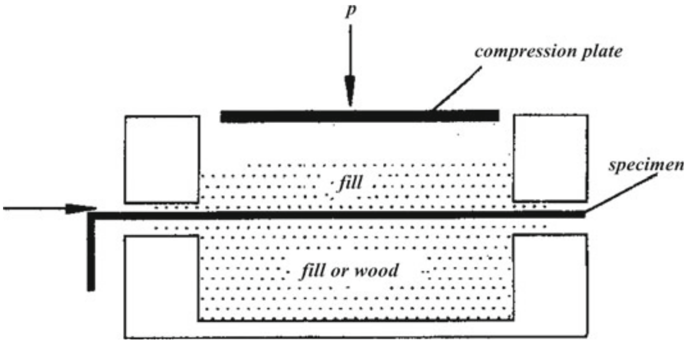

Fig. 2.7 Diagram of the direct shear instrument. Reprinted from Ref. [5], copyright 2001, China Communications Press

drawing chambers or test tanks are developed. Although these two tests reflect the interface friction, the mechanism and the test results are different [8–10].

2.2.3.1 Friction Test of Direct Shear

The friction characteristics on the interface of two materials are often expressed by the adhesion C_a and the friction angle δ or the friction coefficient f^*. The friction shear strength conforms to Coulomb's law and can be expressed as follows:

$$\tau = C_a + p\tan(\delta) = C_a + P \cdot f^* \tag{2.3}$$

τ is the interface shear strength (kPa). C_a is the adhesion force (kPa); δ is the friction angle (°); p is the normal pressure (kPa); and f^* is the friction coefficient.

The friction test of the direct shear is usually carried out under four different pressures p. The corresponding intensity value τ is measured, and then the test results are drawn as lines. The values of C_a, δ, or f^* are finally calculated. The friction angle between the soil and geosynthetics is related to the size, the shape, the tightness, the type of the fabric, the pore size, the thickness of the soil, etc. It is also affected by the positive pressure of the test. According to the test results at home and abroad, the friction angle of the fine-grained soil (such as fine sand, sandy loam, and so on, the soil particle size is less than the fabric pores) and the loose medium particles of soil (such as sand, etc.) with the fabric are close to that of the soil itself. For the coarse-grained soils (such as the coarse sand and the gravel, the particles are generally larger than the pores of the fabric) and the dense fine sand, their friction angles with fabrics are less than the internal friction angles of soils. The friction angle of the soil and the acupuncturing nonwoven fabric is larger. The friction angle of the soil, the geomembrane, and the woven or thermo-boning nonwoven fabric is smaller [11–13] (Fig. 2.7).

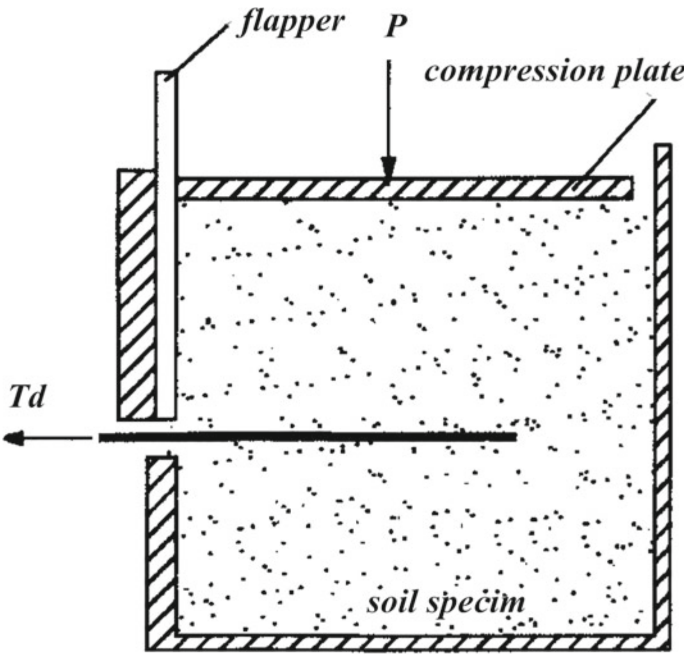

Fig. 2.8 Diagram of the drawing test box. Reprinted from Ref. [5], copyright 2001, China Communications Press

2.2.3.2 Friction Test of Drawing

Geosynthetics buried in the soil is stressed and deformed in the direction of tension when it is subjected to the tension in the direction of its plane. Due to the role of normal stress, the upper and lower interfaces will cause friction resistance when they are pulled. The resistance is not evenly distributed along the direction of tension and varies with the strain of the points. When material is pulled out, it can be considered that the friction resistance of interface is evenly distributed and keep balance with the tension. The value is the friction strength of the interface. The formula is as follows:

$$\tau = \frac{T_d}{2LB} \tag{2.4}$$

where τ is the friction resistance strength of the interface (Pa, kPa). T_d is the instant tension when the fabric sample is pulled out (N, kN). L and B are the length and width of the fabric specimen buried in the soil (m).

The test should be carried out under four different normal stresses p. τ is measured, respectively, and the τ–p curve is drawn. The cohesive force (C_a) and the friction angle (δ) or the friction coefficient (f^*) are calculated from the direct shear test (Fig. 2.8).

2.2.3.3 Influencing Factors of Test Results

According to the literature at home and abroad, the test equipment and test methods of interface characteristics are not unified. The factors considered in various test equipment for testing the characteristics of reinforced materials and the filler interface are different. Factors on the test results are summarized as follows [13–16].

Loading Method

There are two loading methods, including controlling the deformation rate and controlling the load.

Boundary Effect and Size Effect of Rigid Wall of Specimen Box

The friction force of the rigid box wall will reduce the positive pressure on the interface. Through lubricating the box wall of the specimen, the specimen is installed in the flexible film or the width ratio of the reinforced material, and the specimen box is controlled to reduce this effect. The size of the test box should be large enough to ensure that the reinforced materials are far away from the wall on both sides. The tensile test found that the earth pressure between the reinforced specimen and the box wall of specimen on the side of the applied force could increase the interfacial friction resistance so as to affect the test results [13].

Packing Compaction

The friction characteristic of the interface is related to the packing compaction. The friction force between the compact packing and the reinforced material is relatively large. The friction between the loose packing and the reinforced material gradually increases with the dynamic friction process. The adopted compaction method should ensure that the whole compaction degree of the reinforced material is uniform.

Clamping of Reinforced Material

The pull-side clamping outside the specimen box in the drawing test will make the pullout part lose the lateral constraint, which results in changes in the interface area during the test process. The clamping of the reinforced material should ensure that the interface area of the specimen remains unchanged during the drawing process. To achieve this requirement, the free ends of the reinforced material are out of the test box.

Deformation Detection of Reinforced Material

In the drawing test, the test results will be affected by the tensile deformation of the reinforced material. In order to accurately evaluate the interface characteristics and the deformation distribution, some researchers bury the test components in the specimen or the reinforced body to detect the relative deformation or internal force of the different parts.

2.2.4 Hydraulic Characteristic

Geosynthetics such as geotextile, fine geonet, etc. can allow water and air to pass freely, and can effectively intercept and control the loss of soil particles. Therefore, they can be widely used as drainage and filtration materials. Therefore, it is necessary to study its hydraulic characteristic. Hydrodynamic characteristic mainly includes two aspects: the permeability and water conducting capacity, the capacity of preventing the loss of particles. These characteristics mainly include the porosity, the pore size and distribution, and the permeability characteristic of geosynthetics. These characteristics are briefly described below.

The porosity of geosynthetics refers to the ratio of the pore volume to the total volume, which is expressed by n (%). It does not need to be tested directly, but calculated. It is calculated according to the following formula:

$$n = \left(1 - \frac{m}{\rho\delta}\right) \times 100\% \tag{2.5}$$

where m is the mass per unit area (g/m^2), ρ is the density of the raw material (g/m^3), and δ is the thickness of the fabric (m).

The pore size of geosynthetics reflects the permeability of the material and the ability of retaining soil particles, which is an important characteristic index. The sign of the aperture is denoted by O (mm). The distribution of the pore size of the fabric is indicated by an index. For example, O_{95} indicates that the pore size of 95% in the material is below this value. The current measurement of the pore size has direct and indirect methods. The direct method includes the microscopic method and the projection magnification method. The indirect method includes the dry sieve method, the wet sieve method, the hydrodynamic method, the mercury pressure method, the attraction method, the infiltration method, etc.

The permeability of geotextiles is one of the important hydraulic characteristics. In the filtration standards and other related hydraulic design, it is an indispensable indicator. According to the needs of the project, it is often necessary to determine the permeability characteristic which is perpendicular to the plane of the fabric and the permeation characteristic which is parallel to the plane of the fabric. The permeability characteristic which is perpendicular to the plane of the fabric is mainly expressed by the vertical permeability coefficient $\mathrm{k_n}$, which is the seepage flow rate $\mathrm{k_t}$ when the hydrodynamic gradient is equal to 1 and is generally subject to Darcy's law. The permeability coefficient ($\mathrm{k_t}$) along the fabric plane is defined as the infiltration velocity when the hydraulic gradient is equal to 1. The factors on the penetration of geotextiles are complex, including the size of the sample area, the nature of the fabric itself, the type of fabric and the pore distribution, the normal stress on the fabric plane, the water level difference, the water temperature, the bubble content in the water, the performance of the test equipment, and so on.

2.2.5 Durability

The durability of geosynthetics includes many aspects, which mainly refers to the ultraviolet radiation, temperature changes, the chemical and biological erosion, wet and dry changes, freezing and thawing changes, the mechanical wear, etc. The durability of the material is mainly related to the type of polymer and the characteristics of the additive.

The aging phenomenon of geosynthetics is mainly because the polymer has a chain structure, which is affected by external factors and results in the degradation reaction or the cross-linking reaction. The sun radiation is one of the most important factors of the aging. Ultraviolet rays have a lot of energy which can cut off the molecular chains of many polymers or initiate the oxidation reaction. There are mainly two kinds of test methods: the natural aging test and the artificial aging test [17].

2.3 Engineering Application of Geosynthetics

2.3.1 Functions of Geosynthetics and Its Application Scope

The function of geosynthetics is multifaceted. It can be summarized as six functions: the filtration function, the drainage function, the isolation function, the reinforcing function, the anti-seepage function, and the protection function.

2.3.1.1 Filtration Function

The geotextile is placed on the soil surface or between the adjacent soil layers, which can effectively prevent the passage of soil particles so as to prevent the soil damage due to the excessive loss of soil particles. At the same time, the water or gas is allowed to discharge through the fabric so as to avoid the instability of the soil and other adverse consequences caused by the increasing water pressure of pore.

2.3.1.2 Drainage Function

Some geosynthetics can form a drainage channel in the soil. The water in the soil is collected together and drained out of the body along the plane of the material. Thicker acupuncture-type nonwoven fabrics and certain composite geosynthetics with larger pores can act as the drainage.

2.3.1.3 Isolation Function

Some geosynthetics can isolate two different sizes of the soil, sand, and stone. They can also isolate the soil, sand, and stone with foundations or other buildings so as not to be mixed with each other and not to lose various materials and structural integrity or not to lead to the soil erosion. Geotextiles and geomembranes can act as the isolation. They can be used for the isolation layer between the road base and the roadbed or between the roadbed and the foundation.

2.3.1.4 Reinforcing Function

Many geosynthetics are buried in the soil, which can distribute the stress of the soil and increase the modulus of the soil. They can also transfer the tensile stress and limit the lateral displacement of the soil. In addition, it can increase the friction between the soil and other materials and the physical and structural stability of the building. They can be used to strengthen the weak foundation and the stability of the slope. They can also act as the retaining wall to backfill the reinforcement of the soil, or anchor the panel of the retaining wall. In addition, they can build a package retaining wall or abutment, reinforce the flexible pavement, prevent the development of reflection cracks, and so on [18–21].

2.3.1.5 Anti-seepage Function

Geomembrane and composite geosynthetics can prevent liquid leakage and gas volatilization, and protect the environment or the safety of the building, and can be used to earth dam's and reservoir area's anti-seepage, channel seepage, tunnel and culvert, to prevent all kinds of large liquid containers or pool leakage and evaporation, roof leakage, for the construction of coffers and other construction.

2.3.1.6 Protective Function

A variety of geosynthetics on the soil or water can play a protective role. It is mainly used to prevent the river bank or the coast from being washed to prevent garbage, waste or waste liquid being contaminated groundwater or giving off, to prevent the evaporation of water or dust in the air pollution to prevent soil damage, and so on.

2.3.2 Engineering Application of Geosynthetics

2.3.2.1 Isolation

There are two kinds of materials which interact with each other in the civil engineering, such as sand, gravel or gravel base, and soil layer. In order to prevent two materials from penetrating each other, it is necessary to ensure that the structure is expected to function, which can provide the drainage and prevent the deterioration of the bearing capacity of the foundation. A layer of material in the middle is often placed to isolate them. Geotextiles and geomembranes can act as the isolation. They can be located between different sizes of particles and do not mix the coarse and fine particles. They are placed between the building and the weak foundation as the reinforcement at the same time. They can also be located in a variety of roads or sites and foundations.

Design Requirements

As geotextiles and geomembranes of the segregation layer, two requirements must be met. On the one hand, it can prevent the smaller soil particles from intruding into the coarse granular material and maintain certain permeability. On the other hand, it must have sufficient strength to bear a variety of stresses or strains generated by the load. That is, the fabric in any case should not produce the rupture. The porosity, the water permeability, the bursting strength, the puncturing strength, the gripping tensile strength and elongation, the tear strength, and other properties must be calculated to select the appropriate material in design. The specific requirements are determined by the properties of the civil engineering structure, the size, the usage requirements, the load, the construction conditions, and the properties of geosynthetics itself.

Construction Technical Requirements

Geotextiles are laid directly on the surface of the subgrade or the roadway. The protrusions which may damage the fabric in the roadway or the roadbed must be removed. The geotextiles can be then unfolded and laid on the roadbed or the roadway without any fold as possible. If it is necessary to deploy the geotextile over a long distance, it should be fixed to prevent it from blowing around. In the area where the carrying capacity is low, the transverse direction is also fixed. Figure 2.9 is the paving method of geotextile in road engineering.

The connection between the fabrics generally uses the lap and seam methods.

In order to ensure that the geosynthetics in the construction can maintain its integrity, the corresponding construction requirements need to be distributed in terms of the roadbed condition and the embankment filler with the construction machinery.

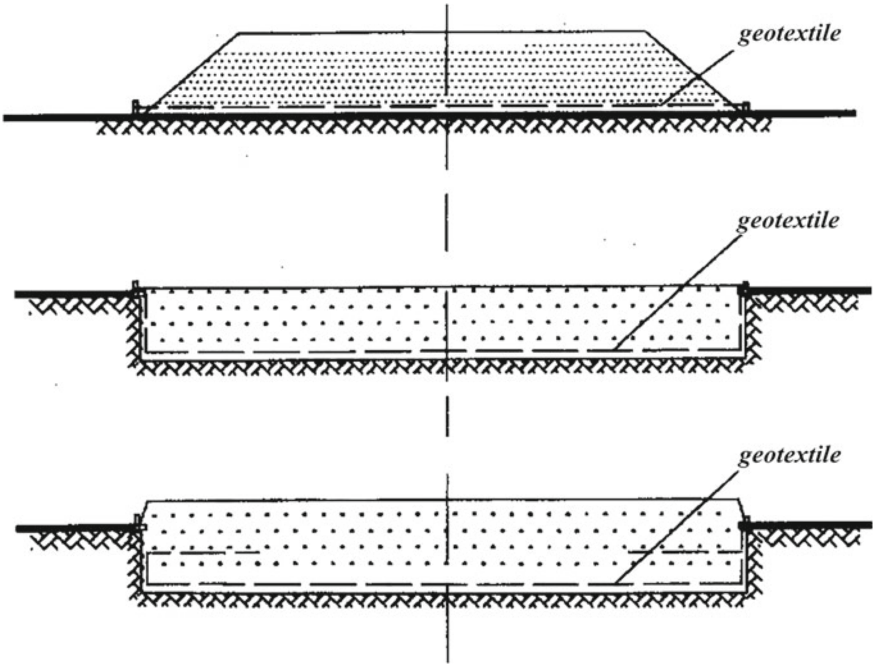

Fig. 2.9 Geotextile paving method in road engineering. Reprinted from Ref. [5], copyright 2001, China Communications Press

2.3.2.2 Engineering Filter

Filter Mechanism

Filtration is also called the reverse filtration or inverted filtration. It refers to the phenomenon that the fluid in the seepage state in the soil flows into the filter material while the solid particles with the role of skeleton are intercepted in the project. Filter material used in the water may lead to the severe deformation of the soil. Filter material is required to retain the earth and maintain the penetration (to keep the water flow).

Function Mechanism

The filter of geotextile with the traditional coarse-grained raw materials (such as gravel) was the same in the early view. Geotextiles with small enough pore size were used to block the particles of the soil in the direction of the earth retaining.

According to the mechanism of induction, geotextiles did not play the role of earth retaining in the filter but induce the soil layer to form a layer of filter near the geotextiles. The filter layer played a role of filtration so geotextiles were considered to only play a role of catalyst.

Usually, it should be a combination of the above only in the different occasions and conditions.

Clogging

Definition

The phenomenon is that with the infiltration of water flow, the fine particles within the protected soil are taken to the internal pores of fabric and intercepted in the fabric surface. After a certain period of time, these particles on the surface or in the internal of the fabric gradually increase, resulting in the decrease of fabric permeability.

Types

The mechanical clogging, the chemical clogging, and the biological clogging.

Factors

The geotextile structure; the soil properties and the particle composition; the hydraulic gradient.

Filter Design of Clogging Test

Design method: to select geotextiles according to the test method; to design according to the filter criteria which comes from the test results, the traditional theory, and their combination.

Earth retaining (soil conservation performance) criteria:

a. Static load and one-way flow

   (a) the non-cohesive soil (coarse soil) (particles size: $d < 0.075$ mm, particle content: <50%):

$$O_{95} < d_{85} \tag{2.6}$$

   (b) the cohesive soil (fine soil) (particle size: $d < 0.075$ mm, particle content: >50%):

$$O_{95} < 0.21\,\text{mm} \tag{2.7}$$

b. the static load and the two-way flow (seepage):

   (a) soil particles: when $d_{40} < 0.06$ mm

$$O_{95} < 1.3d_{90} \tag{2.8}$$

   (b) soil particles: when $d_{40} \geq 0.06$ mm

$$O_{95} < 2d_{10}\sqrt{C_u}, \tag{2.9}$$

$$\text{and}\, O_{95} < 1.3d_{50}, \tag{2.10}$$

$$C_u = \frac{d_{60}}{d_{10}}\ \text{And}\, O_{95} < 0.67\,\text{mm(at the same time)} \tag{2.11}$$

C_u	the heterogeneity coefficient of soil particle,
O_{95}, O_{90}	the equivalent pore size (mm). There are 95, 90% soil particles whose pore sizes are less than that or the 95, 90% pore size below this value in the pore size distribution curve of geotextile.
d_{10} … d_{85}	In the sieving curve of soil particles, the mass of the soil particle whose size is less than that, respectively, occupies 10 … 85% of the total mass or is less than the mass percentage of certain size *di*. Generally, d_{60} is a limited particle size. d_{50} is an average particle size. d_{10} is an effective particle size

c. the dynamic load:

Bell criteria: $O_{95} < d_{85}$
The standard of China's Ministry of Railways:
prevent piping: $O_{95} < d_{85}$; ensuring penetration: $O_{95} > d_{15}$; well-distributed filter: $O_{95} < 2d_{50}$.

Permeation Criteria of Clogging Test

According to the characteristic diameter of the geotextile and the characteristic particle size of the protected soil, a certain relationship is established: $O_{90} > d_{15}$.

The coefficient criteria of geotextile permeability is

$$k_{\mathrm{g}} \geq \lambda_p k_{\mathrm{s}} \tag{2.12}$$

where

k_{g}	the permeability coefficient of geotextile (cm/s);
k_{s}	the permeability coefficient of soil (cm/s);
λ_p	the nonfactor coefficient, 10–100 for the cohesive soil; 1–10 for the sandy soil. It generally takes $\lambda_p = 10$, which contains the safety factor of the meaning and considers the impact of clogging

Example:

Try to judge whether the geotextile filter for the soil (sand) protection used in a project is appropriate. The geotextile O_{95} is 0.1 mm. The vertical permeability coefficient is 2.62×10^{-2} cm/s. The soil particle components are shown in Table 2.1. The permeability coefficient is 9.38×10^{-4} cm/s.

Table 2.1 The soil particle components

Particle components								Limit particle size	Effective particle size	Average particle size	Limit particle size	
d (mm)	0.25	0.20	0.154	0.10	0.076	0.05		d_{60}	d_{10}	d_{50}	d_{85}	d_{15}
%	0.90	1.0	7.8	11.2	12.1	19.5	43.5	0.071	0.006	0.050	0.150	0.009

Solution: the static load and the one-way flow:

Because the mass percentage is greater than 50% when $d < 0.075$ mm, $O_{95} < 0.21$ mm.

the static load and the two-way flow:

Because $d_{40} = 0.034$ mm < 0.06 mm, $O_{95} < 1.3d_{90} = 1.3 \times 0.18 = 0.234$ mm.

2.3.2.3 Drainage

The drainage can reduce and control the water level in the soil, accelerate the reduction of excess hydrostatic pressure in the pore water, and control the location of the water seepage. Its main purpose is to increase the stability of the soil. The drainage capacity of geotextile (permeable) is very strong because of its high porosity. For example, the porosity of the nonwoven fabric can be up to 90% while the gravel porosity is generally not more than 50%. The vertical drainage is in soft soil-reinforced foundation.

The preloading and drainage board are often combined to drain. The principle of drainage and preloading reinforced foundation is that the load which is equal to or more than the design load is applied to the surface of the soft base. After the preloading in the construction period, the majority (such as 80%) or most (such as 90–95%) of the settlement is completed by the soft base. After the completion of preloading, the preloading is unloaded and the foundation rebounded. After the delivery, the foundation bears the load and resettles but the amount of settlement is very small (it is only the amount of resilience during the unloading plus the amount of residual settlement, which has no effect on the use and safety of the building). The purposes of reducing the foundation settlement after the construction and improving the bearing capacity of the foundation are reached.

Preloading is divided into the surcharge preloading method and the vacuum preloading method (using atmospheric pressure).

The selection and requirements of design parameters: the design method is in accordance with the sand well drainage method.

Range and Depth of Board Drainage

Their factors include the impact of the load on the range and depth of the foundation, the soft soil distribution, the limit depth of construction machinery, and so on. Generally, the depth below 20 m is appropriate, while it is up to 40 m ($d_{\max}$) abroad. It generally should reach the bottom of the soft soil layer. If the soft soil is thicker (2 times more than the width of the building), the arc sliding surface calculated by the soil stability must be penetrated at least 2 m.

Layout

The positive triangle or square.

Equivalent Diameter of Cylinder of Flat Drainage Board

dw (drainage effect and drainage preloading effect of 7 cm bagged sand well)

$$\mathrm{dw} = a \cdot \frac{2(b + \delta)}{\pi} \tag{2.13}$$

where

b	the width of drainage board;
δ	the thickness;
a	coefficient (0.75–1.0).

Equivalent round diameter of drainage range of drainage board: de. The equilateral triangle layout is 1.05 L. The square layout is 1.13 L. L is the spacing of drainage board.

Preloading Time

It is determined by the theoretical formula or graph method.

The theoretical formula: the ideal well (the reinforced depth is less than 15 m without considering the construction deflection and smearing effect (with the intubation, the tightening of the soil impacts the drainage). It should be calculated when the reinforced depth is more than 15 m according to the nonideal well design)

$$t = \frac{\mathrm{de}^2}{8C_h}(\ln\frac{\mathrm{de}}{\mathrm{dw}} - 0.75)\ln\frac{1}{1 - \bar{U}_h} \tag{2.14}$$

where

de	the equivalent round diameter of drainage range (m);
dw	the effective round diameter of drainage board (m);
C_h	the horizontal consolidation coefficient (radial) (m^2/s);
$\bar{U}_h$	the average degree of consolidation of horizontal radial drainage (when the load is applied instantaneously);
$\bar{U}_h = \bar{U}_{hz}$	(total average consolidation degree);
$\bar{U}_{hz} = 1 - (1 - \bar{U}_z)(1 - \bar{U}_h) = \bar{U}_h$	(because the spacing of drainage board is much smaller than the thickness of soft soil).

Design example

The preloading and plastic drainage board is used to reinforce the 10-meter-thick soft soil in a construction. The average consolidation degree of the soft soil is required to be 80%. Calculate the preloading time. The horizontal consolidation coefficient of the soft soil is 4.8×10^{-8} m^2/s. The drainage board area is 100 mm × 3 mm. According to the square layout, the spacing of drainage board is 1.3 m.

Horizontal drainage of the foundation surface

Standard of horizontal drainage for the foundation surface

Requirement:

$$q_e \geq q \tag{2.15}$$

where

q the discharged water per meter which is vertical to the direction of water seepage (m^2/s);

q_e the drainage capacity of the effluent section of geotextile and plastic drainage board per meter (m^2/s);

$$q_e = \beta \frac{\Delta hg}{L_{\mathrm{G}}} \cdot \frac{\theta_{\mathrm{G}}}{F_d} \tag{2.16}$$

where

β the layout-type coefficient of geotextile and plastic drainage board. That is, the width of layout each meter. When the layout is full, $\beta = 1$; when it is the strip type, $\beta = \frac{\sum B_i}{1.0}$, $\sum B_i$ is the sum of the strip width per meter;

θ_{G} the hydraulic conductivity of geosynthetics (m^2/s) is determined by the experiment;

L_{G} the geosynthetics length in the flowing direction (m) (the drainage length);

Δhg the head difference of the first end along the drainage layer [length (L_{G})], that is, the head loss (m);

$$\Delta hg = \alpha \frac{p}{\gamma_w}$$

where

α the loss coefficient of water head, $\alpha = 0.01$–0.1;

γ_{w} the weight of a unit volume of water, 10 kN/m^3;

P the additional compressive stress (kN/m^2) (the even load can be seen as being evenly distributed along the depth);

F_d the safe reserving coefficient of considering the block. $F_d = 10$ or it is determined by the test.

Design example

A embankment in the soft foundation is to be constructed. The bottom of the embankment is to be laid with the geotextile drainage layer, which can drain along two horizontal directions. The bottom of the embankment is 30 m long. The pressure at the bottom of the embankment is 8 kN/m^2. The head loss coefficient is 0.05. If the water conductivity of geotextile is 5×10^{-5} m^2/s, the geotextile is full of the bottom of the embankment. Can it meet the requirement of the discharge of water flow per meter?

Solution:

- the calculation and selection of relevant parameters
  $L_{\mathrm{G}} = \frac{1}{2}$, $L_b = \frac{30}{2} = 15\mathrm{m}$, $\gamma_w = 10\,\mathrm{kN/m^3}$, $\beta = 1$, $P = 8\ \mathrm{kN/m^2}$, $\theta_G = 5 \times 10^{-5}\mathrm{m^2/s}$, $\alpha = 0.05$

$$\Delta hg = \alpha \frac{p}{\gamma_w} = 0.05 \times \frac{8}{10} = 0.04\,(\mathrm{m})$$

- Calculation

$$q_e = \beta \cdot \frac{\Delta hg}{L_{\mathrm{G}}} \times \frac{\theta_G}{F_d}$$

$$\text{The water flow per meter} = 1 \times \frac{0.04}{15} \times \frac{5 \times 10^{-5}}{10} = 1.33 \times 10^{-8}\mathrm{m^2/s}$$

- Comparison

q_e >q, so it can meet the requirement.

Exercises

1. Briefly describe the advantages of geotextile compared with the drainage materials of traditional filter.
2. What is the filtration? What requirements should the filter layer design meet?
3. Try to judge whether the geotextile filter for the soil (sand) protection used in a project is appropriate. The geotextile O_{95} is 0.1 mm. The vertical permeability coefficient is 2.62×10^{-2} cm/s. The soil particle components are shown in Table 2.2. The permeability coefficient is 9.38×10^{-4} cm/s.
4. An embankment in the soft foundation is to be constructed. The bottom of the embankment is to be laid with the geotextile drainage layer, which can drain along two horizontal directions. The bottom of the embankment is 30 m long. The pressure at the bottom of the embankment is 10 kN/m^2. The head loss coefficient is 0.08. If the water conductivity of geotextile is 1.6×10^{-8} m^2/s, what is the minimum water conductivity of geotextile?
5. The preloading and plastic drainage board is used to reinforce the 10-m-thick soft soil in a construction. The average consolidation degree of the soft soil is required to be 80%. Calculate the preloading time. The horizontal consolidation coefficient of the soft soil is 4.8×10^{-8} m^2/s. The drainage board area is 100 mm × 3 mm. According to the triangle layout, the spacing of drainage board is 1.3 m (a = 0.8).

Table 2.2 The soil particle components

Particle components								Limit particle size	Effective particle size	Average particle size	Limit particle size	
d (mm)	0.25	0.20	0.154	0.10	0.076	0.05		d_{60}	d_{10}	d_{50}	d_{85}	d_{15}
%	0.65	1.0	12.4	46.2	29.7	4.55	5.5	0.117	0.076	0.108	0.153	0.083

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Chapter 3
Steel Fiber Reinforced Concrete

3.1 Material Components and Process Characteristics of Steel Fiber Reinforced Concrete

3.1.1 Components

3.1.1.1 Steel Fiber

(a) **Classification**

According to the Fiber Shape

Long straight, indented, wavy, hook-shaped, big head shape, twisted;

According to the Production Process of Steel Fiber

Cut-off type (wire is cut with its 600–3000 MPa strength), sheared type (thin steel plate is sheared with its 380–800 MPa strength), milling type (380–800 MPa) and melting type (380–800 MPa);

According to Materials

Ordinary carbon steel fiber and stainless steel fiber;

According to the Usage

Pouring and spraying.

(b) **Main Performance of Steel Fiber**

Tensile Strength

According to the common damage (pull-out damage), the maximum tensile stress of damage is 100–300 MPa. The tensile strength of single steel fiber in highway

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Table 3.1 Selection table of geometry parameters of steel fiber

Structure types of steel fiber reinforced concrete	Length (mm)	Diameter (equivalent diameter) (mm)	Aspect ratio
General structure of pouring molding	25–60	0.3–1.2	40–100
Frame seismic node	40–60	0.4–1.2	50–100
Railway sleeper	20–30	0.3–0.6	50–70
Spraying steel fiber reinforced concrete	15–25	0.3–0.5	30–60

Table 3.2 Selection table of volume ratio of steel fiber

Structure types of steel fiber reinforced concrete	Volume ratio of steel fiber (%)	Structure types of steel fiber reinforced concrete	Volume ratio of steel fiber (%)
General structure of pouring molding	0.5–2.0	Railway sleeper, rigid waterproof roof	0.8–1.2
Local compression components, bridge deck, prefabricated pile top, pile tip	1.0–1.5	Spraying steel fiber	0.5–1.5

engineering should not be less than 600 MPa. The level of steel fiber is divided according to the tensile strength. The steel fiber is generally divided into three grades: 380 MPa, 600 MPa, 1000 MPa.

Bonding Strength

It is measured according to the direct drawing method. Measures to improve the bond strength: to roughen the surface and become a variable cross-section; to increase the contact surface and friction with the matrix; to indent the surface of steel fiber or to press it into a waveform; to increase the mechanical bond force; to make the end of steel fiber heteromorphic.

Firmness

It must be hard enough to avoid the deformation in mixing.

Corrosion Resistance

It can resist the erosion in the corresponding environment.

Geometric Parameters and Volume Ratio of Steel Fiber

The geometrical parameters of steel fiber are length, diameter, the aspect ratio ($\frac{l_f}{d_f}$). The common engineering requirements are shown in Tables 3.1 and 3.2 [1, 2].

Table 3.3 Requirements for geometry parameters and shape accuracy of steel fiber

Types of construction	Length mm	Qualified rate of Length (%)	Diameter (equivalent diameter) (mm)	Qualified rate of shape (%)	Aspect ratio	Deviation of average and standard numbers of steel fiber (%)
Pavement and bridge deck of mixed steel fiber reinforced concrete	20–35	>90	0.3–0.8	>90	30–80	±10
Pavement of layered steel fiber reinforced concrete	80–150	>95	0.3–1.2	>85	125–500	±10

Note The test method of geometric parameters and shape accuracy of steel fiber should comply with the provisions of YB/T151

The requirement in the highway engineering: $l_{f\,\min} \geq \frac{1}{3} d_{\max}$, $l_{f\,\max} \leq 2d_{\max}$

l_f is the length of steel fiber. $d_{\max}$ is the maximum size of the aggregate.

Geometry parameters and shape accuracy of steel fiber used in pavement and bridge deck concrete should meet the requirements of Table 3.3.

3.1.1.2 Cement

It is used largely with the strength of 32.5, generally 360–450 kg/m^3. It is the ordinary Portland cement of grade 42.5.

3.1.1.3 Sand

The coarse sand is appropriate. It is easy to segregate and weep for too coarse sand. It must increase the amount of cement for too fine sand.

3.1.1.4 Stone

The gravel is often selected. The maximum particle size ($d_{\max}$) is not more than 20 mm, and 2/3 of the size of steel fiber. It is not easy to disperse with large $d_{\max}$. The aggregate gradation should meet the requirements otherwise it will affect the flow of mixed material of steel fiber reinforced concrete and the amount of cement.

3.1.1.5 Water

It can be used in the ordinary concrete but the seawater cannot.

3.1.1.6 Addictive

The water-reducing addictive is widely used, which can improve the workability.

3.1.2 Characteristics of Mixed Materials of Steel Fiber Reinforced Concrete

3.1.2.1 Dispersion Uniformity of Steel Fiber in the Concrete

Dispersion Coefficient (β)

Dispersion non-uniformity: weaken the effect and decrease the local strength.

According to a Japanese scholar [6], the dispersion coefficient β is used to describe the dispersion uniformity of steel fiber (when it is evenly distributed $\beta = 1$; $\beta = 0$ without the steel fabric). The formula of dispersion coefficient is shown in Eq. 3.1.

$$\beta = \mathrm{e}^{\phi(x)} \text{ (mathematical statistics index function)} \tag{3.1}$$

β is the dispersion coefficient: $\phi(x) = \sqrt{\frac{\Sigma(x_i-\mu)^2}{n}}/\mu$

μ the average number of fibers contained in the sample;

n the number of segments (the number of samples);

x_i the number of fibers contained in the segments i.

Influencing Factors of Dispersion Uniformity

- Volume ratio, the aspect ratio and variety of steel fiber
  The best volume ratio is 1.5% (the largest dispersion coefficient), it is appropriate for $V_f = 1 - 2\%$. If $l_f/d_f > 100$, it is easy to cluster. If $l_f/d_f < 60$, it is not easy to cluster. Variety: the melting type and the milling type with larger hardness are easy to disperse.

- $d_{\max}$: 15 mm is appropriate. If too large, it is not easy to be even.
- Sand ratio, the water-cement ratio, the water consumption
  When $d_{\max}$ and V_f keep unchanged, the sand rate and the dispersion coefficient increase. When W/C and water consumption increase, the dispersion coefficient increase.
- Mixing machine and the feeding method: it is used to avoid clustering.

3.1.2.2 Workability

Evaluation Method [3, 4]

The slump method (not less than 20 mm). V_B(S)(> 10 S). the inverted slump cone method (<20 mm, <10 S).

Influencing Factors

- The volume ratio and aspect ratio of steel fiber
  The slump decreases with the increase of V_f. When l_f/d_f increases, the slump decreases.
- The amount of cement slurry: the workability increases with the increase of the amount. The appropriate amount is $m_c = 360$–$450\ \text{kg/m}^3$.
- The consistency of cement slurry: it is appropriate when $W/C = 0.40$–0.50.
- The sand ratio: it affects the total surface area of porosity and aggregate. The aggregate which is less than 5 mm is conducive to the fiber movement. The best sand ratio ranges from 40 to 50%.
- The aggregate characteristic: $d_{\max}$ is too large, resulting in the fiber clustering in large particles.
- The addictive and gas content. The gas content which is less than 6% is appropriate. When the vibrating is dense, its gas content is as same as ordinary cement concrete.

3.2 Reinforcing Mechanism and Interface Performance of Steel Fiber Reinforced Concrete

3.2.1 Reinforcing Mechanism of Steel Fiber Reinforced Concrete

There are two main theories for the reinforcing mechanism of steel fiber reinforced concrete: the composite mechanics theory and the fiber spacing theory (or fiber crack resistance theory) [6].

3.2.1.1 Composite Mechanics Theory

The steel fiber reinforced concrete is regarded as a kind of fiber strengthening system. The stress, elastic modulus and strength of steel fiber reinforced concrete are deduced by the rule of mixture. The fiber direction coefficient (η_0) and fiber length coefficient (η_1) are introduced. The proportion of the volume ratio of effective fiber in the tensile stress direction and the non-uniform distribution of the non-continuous short fiber stress along the fiber length are considered.

In the approximate elastic deformation range before the cracking of the concrete matrix, the stress of the steel fiber reinforced concrete is calculated as follows:

$$\sigma = \sigma_m \rho_m + \eta_0 \eta_1 \sigma_f \rho_f \tag{3.2}$$

where

σ the stress of steel fiber reinforced concrete;
σ_m the stress of concrete;
ρ_f the volume ratio of steel fiber;
ρ_m the volume ratio of concrete, $\rho_m = 1 - \rho_f$.

When the strain of the concrete reaches the cracking strain ($\varepsilon_{\mathrm{tu}}$) of the matrix, visible microcracks in the concrete appear. The stress reaches the tensile strength (f_t) of the concrete. $E_f \varepsilon_{\mathrm{tu}}$ is the corresponding stress of steel fiber. The relative slip between the steel fiber and the concrete appears and the steel fiber starts to pull out. The cracking strength of steel fiber reinforced concrete is calculated as follows:

$$f_{fcr} = f_t \rho_m + \eta_0 \eta_1 E_f \varepsilon_{tu} \rho_f \tag{3.3}$$

Due to the crack resistance and reinforced effect of steel fiber, the steel fiber concrete does not destroy immediately after the visible cracks appeared in the concrete matrix. With the steady development of the crack, the stress continues to increase until the crack width increases to a certain extent. The steel fiber is pulled out gradually. The instability and destruction of crack appear in the steel fiber reinforced concrete. At this time, if τ is the average bonding stress of the steel fiber and the concrete, the stress of the steel fiber is calculated as follows:

$$\sigma_f = \eta_0 \tau \frac{l_f}{d_f} \tag{3.4}$$

where

σ_f the length of the steel fiber (mm);
d_f the diameter of steel fiber (mm).

$\sigma_m = f_t$, $\eta_1 = 1$ and Eq. 3.4 are put into Eq. 3.2. The formula for calculating the tensile strength of steel fiber reinforced concrete according to the composite mechanics theory is obtained as follows:

$$f_{ft} = f_t(1 - \rho_f) + \eta_0 \tau \frac{l_f}{d_f} \rho_f \tag{3.5}$$

The correctness of Eq. 3.5 has been verified by a large number of test results.

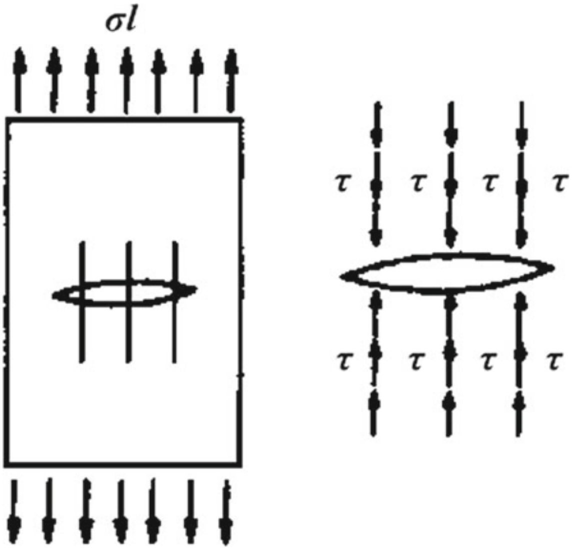

Fig. 3.1 Crack resistance and reinforcing mechanism of steel fiber. Reprinted from Ref. [4], copyright 2002, China Architecture and Building Press

3.2.1.2 Fiber Spacing Theory

The binding effect of steel fiber on the occurrence and development of cracks is explained by the fiber spacing theory according to the principle of linear elastic fracture mechanics. According to the theory, it is necessary to reduce the size of the internal defects as much as possible and to reduce the strength factor of stress field of the crack tip in order to enhance the tensile characteristic of the inherently brittle concrete.

It is used to study the mechanism of the uniaxial extension of steel fiber reinforced concrete, which is shown in Fig. 3.1. For brittle materials such as the concrete, weak links exist between the fine aggregate interface area (cement slurry) and the coarse aggregate interface area (sand slurry). Although the components of materials have a high tensile strength, the macro-tensile strength is very low so that the broken damage in the concrete generally exists. The addition of steel fibers can cross both sides of the fracture so that the bond stress between the steel fibers and the concrete on both sides of the fracture play a role of resisting the crack shown in Fig. 3.1. Assuming that K_σ is the strength factor of stress which causes the internal crack, K_f is the strength factor of stress in the reverse stress field which is constrained by the bond stress distribution (τ) near the fracture end. The total stress strength factor K_I reduces shown in Eq. 3.6.

$$K_I = K_\sigma - K_f < K_\sigma \tag{3.6}$$

From the Eq. 3.6, the more the fiber across the cracks or the number of fibers per unit area is, the bigger the crack resistance and the reinforcement of steel fiber are.

For the uniaxial extension of steel fiber reinforced concrete, the stress field of open crack (type I) is briefly described by Fig. 3.1. The calculation formula of strength factor of crack tip stress field is shown in Eq. 3.7.

$$K_I = y(\sigma - \overline{\sigma}_f)\sqrt{a} \tag{3.7}$$

where

K_I the strength factor of stress field at the tip of the I-type crack, which reflects the strength of the stress field in the local area of the crack tip;

y the geometric factor, which is mainly related to the geometry, size and loading methods of the cracks. For the central penetrating cracks, $y = \sqrt{\pi}$;

σ the tensile stress generated by load;

$\overline{\sigma}_f$ the average tensile stress of steel fiber. According to the composite mechanics theory, $\overline{\sigma}_f$ is calculated by the following formula combined with the Eq. 3.4.

$$\overline{\sigma}_f = \eta_0 \tau \frac{l_f}{d_f} \rho_f \tag{3.8}$$

where

a the half crack length.

According to the fracture mechanics theory, the steel fiber concrete breaks down when the strength factor of stress field of the crack tip reaches the fracture toughness of the concrete. The tensile stress (σ) of the steel fiber concrete reaches its tensile strength (f_{ft}) shown in Eq. 3.9.

$$K_I = y\sqrt{a_c}(f_{ft} - \overline{\sigma}_f) = K_{IC} \tag{3.9}$$

where

a_c the critical half-crack length when the crack is extended due to the instability;

K_{IC} the fracture toughness of concrete. That is, the strength factor of critical stress. The formula is shown in Eq. 3.10.

$$K_{IC} = y\sqrt{a_c}\overline{\sigma}_m \tag{3.10}$$

where

$\overline{\sigma}_m$ the average tensile stress of concrete matrix when the steel fiber reinforced concrete fractures. When it fractures, the concrete reaches the tensile strength (f_t). According to the composite mechanism theory, the calculation formula of the average tensile stress of the concrete under the damage section is shown in Eq. 3.11.

$$\overline{\sigma}_m = f_t \rho_m \tag{3.11}$$

The formula for calculating the tensile strength of steel fiber reinforced concrete Eq. 3.5 is obtained by combining with Eqs. 3.9, 3.10 and 3.11.

Unified computing model of strength

Assuming that f_t is the strength of the steel fiber reinforced concrete, f_m is the strength of the concrete matrix. τ is the average bond strength between the steel fiber and the concrete. η_0 is the fiber direction coefficient. The uniform calculation mode of the strength index is obtained by the Eq. 3.5.

$$f_f = f_m(1 - \rho_f) + \eta_0 \tau \rho_f \frac{l_f}{d_f} \tag{3.12}$$

As $\rho_f = (1\text{–}2\%)$ (the volume ratio of steel fiber reinforced concrete fiber), $1 - \rho_f$ is approximately equal to 1. The following formula is obtained.

$$f_f = f_m\left(1 + \eta_0 \frac{\tau}{f_m} \rho_f \frac{l_f}{d_f}\right) \tag{3.13}$$

Because $\alpha = \eta_0 \frac{\tau}{f_m}$ and $\lambda_f = \rho_f \frac{l_f}{d_f}$, Eq. 3.13 is transformed into Eq. 3.14.

$$f_f = f_m(1 + \alpha \lambda_f) \tag{3.14}$$

where

λ_f the characteristic parameter of steel fiber content;
α the parameter which is related to type, shape, distribution and force model of steel fiber. Its value is determined by the statistical data.

Equation 3.14 is a unified calculation model for various indicators of steel fiber reinforced concrete strength.

3.2.2 *Steel Fiber—Interface Performance of Cement Base*

3.2.2.1 Steel Fiber—Interface Formation and Characteristics of Cement Base

According to Maso's hypothesis of interface formation mechanism, a water film layer is formed on the surface of the steel fiber and the aggregate in mixing. The thickness is only a few to dozens of microns. The concentration of cement particles which are close to the surface of fiber or aggregate is close to 0. It increases with the increase of distance from the surface of fiber or aggregate.

According to the degree of ion activity $Na^+ > K^+ > SO_4^{2-} > Ca^{2+} > Si^{4+}$, it enters into the water film in order. The first hydrated product of the water film is a crystal phase(the Portland cement which produces ettringite and calcium hydroxide) made up from ions that first diffuse into the water film layer.

3.2.2.2 Interface Characteristics Between the Steel Fiber and the Cement Base

The water-cement ratio is higher than that of the matrix;
The porosity is higher than that of the matrix;
The structure of interface layer is a loose network (due to the high porosity, it is not good for the surface contact of C-S-H and the steel fiber so that the number of C-S-H is small.);
The thickness of interface layer is generally 50–100 μm. Its value changes with the interface structure. In the interface layer, there is a weakest area, which is also known as the weak valley.

3.2.2.3 Main Parameters of Judging Characteristics of Interface Layer

The crystal orientation of $Ca(OH)_2$ (orientation index and orientation range).
The average size and its distribution curve of $Ca(OH)_2$ and Aft (ettringite).
The microhardness distribution and the interface layer thickness.
The pore structure of interface layer.

3.2.2.4 Reinforcement, Disappearance, Reinforcing Process and Mechanism of Interface Layer

The main indicators of improving the interface structure and characteristics include: reducing the crystal orientation, refining the average size of the crystal, improving the microhardness value and the pore structure of the interface layer, etc.

The factors (to improve the interface):

- To reduce the W/C, resulting in a reinforced effect but there is still interface layer.
- To increase V_f, which can improve the interface structure.
- To add the addictive: the composite approach of granular material is adopted, that is, the incorporation of different amounts of organic polymers, inorganic silica fume and their composites in the cement matrix. It is possible to make the interface layer from reinforcing to disappearing.
- Silica fume: it is composed of amorphous spherical vitreous SiO_2 (90–95%) of high content. It has a huge surface area (generally up to 20–26 m^2/g), which is 60–70 times more than that of cement. The particle size is 0.01–1.0 μm, which is 1/100–1/50 of the size of the cement particle. The particles which are less than

0.1 μm occupy 70%. These very fine glass balls have a high activity, which have two functions in the cement matrix: (a) the filling effect. The silica fume particles are two orders of magnitude smaller than the cement particles. Thus, it can be filled in the voids between the cement particles (physical filling). (b) the volcanic ash effect (secondary reaction). $Ca(OH)_2$ reacts with SiO_2 in the silica fume to generate C-S-H, which thereby blocks the pores and cuts off the micro-crack connectivity of interface layer so that the structure of interface layer becomes dense (secondary filling); (c) The interface effect. The secondary reaction and silica fume mortar do not bleed. The interface does not exist on the water film, which reinforces the bonding force of the interface.

- The Polymer: good water reduction effect (such as acrylic copolymer emulsion(APE), the water reduction rate(>40%)), adhesion effect and film effect. There is a strong sticky capacity between the polymer and steel fiber (or aggregate). The water in the polymer is absorbed in the hydration process of cement matrix. After the consolidation, the polymer becomes a polymer film deposited in a cement matrix, which forms a continuous phase with the cement matrix in the interface layer. Therefore, the concentration degree of stress on the crack tip is relieved and the internal stress state of the interface layer is improved. The initiation and expansion of the crack are restricted, and the interface layer is reinforced.

3.3 Performance of Steel Fiber Reinforced Concrete

3.3.1 Mechanical Performance of Steel Fiber Reinforced Concrete

3.3.1.1 Compressive Strength

The performance and volume ratio of steel fiber have a small influence on the compressive strength. The compressive strength is not a main indicator of steel fiber reinforced concrete but according to the standard value of compressive strength, the strength grades of steel fiber reinforced concrete are divided into 13 grades: CF20, CF30, CF35, CF35, CF40, CF45, CF50, CF55, CF60, CF65, CF70, CF75 and CF80 [2].

3.3.1.2 Bending Strength

When there is a bending load, the bending strength must be considered in the engineering and products, such as road, bridge, sleepers. The trabecular (150 mm × 150 mm × 550 mm)is generally used to determine the bending strength by the bending test [3].

The bending strength of steel fiber reinforced concrete is calculated as follows:

Table 3.4 Reference value of impact coefficient of steel fiber on bending strength varieties

Types of steel fiber	Shapes of fiber	Grades of strength	α_{tm}	α_t
Cut-off type of high-strength steel wire	Hook	CF20–CF45	1.13	0.76
		CF50–CF80	1.25	1.03
Shear type of steel plate	Flat and straight	CF20–CF45	0.68	0.42
		CF50–CF80	0.75	0.46
	Abnormal	CF20–CF45	0.79	0.55
		CF50–CF80	0.93	0.63
Steel ingot milling	Hook	CF20–CF45	0.92	0.70
		CF50–CF80	1.10	0.84
Abnormal type of low-alloy steel melting and pumping	Large head	CF20–CF45	0.73	0.52
		CF50–CF80	0.91	0.62

Note Bending strength (axial tensile strength) of plain concrete with the same grade of strength refers to the bending strength (axial tensile strength) of plain concrete with the same composite material, water-cement ratio and similar consistency (water consumption and sand ratio can be properly adjusted) as these of steel fiber reinforced concrete

$$f_{ftm} = f_{tm}(1 + \alpha_{tm}\rho_f \cdot \frac{l_f}{d_f}) = f_{tm}(1 + \alpha_{tm}\lambda_f) \tag{3.15}$$

where

λ_f the characteristic parameters of fiber;
α_{tm} the influence coefficient of steel fiber on bending strength determined by Table 3.4;
f_{ftm} the average value of bending strength of steel fiber reinforced concrete (MPa);
f_{tm} the average value of bending strength of ordinary concrete (MPa).

3.3.1.3 Shear Strength

The beam specimen of 100 mm × 100 mm cross-section (the length is 2–4 times more that the height) is used to do the double-sided direct shear test. The statistical formula of shear strength is as follows:

$$f_{f\tau} = f_\tau(1 + \alpha_\tau\lambda_f) = f_\tau(1 + 0.55\lambda_f) \tag{3.16}$$

where

λ_f the characteristic parameters of fiber;
α_τ the influence coefficient of steel fiber on shear strength is 0.55;
$f_{f\tau}$ the average value of shear strength of steel fiber reinforced concrete (MPa);
f_τ the average value of shear strength of ordinary concrete (MPa).

The mechanism of the shear strength is similar to that of the bending strength, but the increase of the shear strength is greater. In the shear component, the amount of shear steel can be appropriately reduced in order to achieve the purpose of saving steel. It is mainly used for the special structures such as thin-walled shape, seismic shape and complex shape.

3.3.1.4 Axial Tensile Strength of Steel Fiber Reinforced Concrete

The direct tensile test for the steel fiber reinforced concrete is the same as the ordinary concrete in the test. The operation is complex so that it is difficult to center. The specimen is not often pulled by the axis but the eccentric tensile damage. The damage section sometimes does not occur in the specified gauge so that the test results fluctuate greatly. At home and abroad, the tensile strength of steel fiber reinforced concrete is measured by the splitting method. The test operation is simple and easy to control so that the results fluctuate slightly and have good correlation the volume ratio and the aspect ratio of the steel fiber. Therefore, *The Test Methods of Steel Fiber Reinforced Concrete* (CECS13: 89) uses the splitting method as a standard test method for the tensile strength of the steel fiber reinforced concrete. The ACI544 Committee of USA also uses the splitting test method for the steel fiber reinforced concrete.

The test method of splitting tensile strength of steel fiber reinforced concrete is basically the same as that of the ordinary concrete. A cube with a side length of 150 mm is used as the standard specimen [5, 7].

The statistical formula is as follows:

$$f_{f\tau} = f_{c\tau}(1 + \alpha_\tau \lambda_f) \tag{3.17}$$

where

f_{ft} the average value of the axial tensile strength of the steel fiber reinforced concrete;

f_{ct} the average value of the axial tensile strength of the concrete with the same grade. Because it is relatively difficult to focus the axis, the splitting tensile strength is generally used to calculate the axial tensile strength;
$f_{ft} = 0.85 f_{fts}$ (the splitting strength). $f_{fts} = 0.637\,\frac{P}{A}$($P$ is the splitting failure load and A is the corresponding splitting area).

α_t the influence parameter of steel fiber on the tensile strength of concrete. It is determined according to Table 3.4.

3.3.1.5 Impact Resistance of Steel Fiber Reinforced Concrete

The impact resistance of steel fiber reinforced concrete is the ability of absorbing the kinetic energy of composite materials under the repeated impact load. Compared with the ordinary concrete, both the impact strength and the impact toughness improve.

Test Method:

Falling Ball Impact Test

The stamping impact test (ACI544 (USA)); the weight of the impact hammer (4.5 kg); the falling height of the impact hammer of 457 mm. The four indices are tested. The first one is that the number of impact of the first crack occurs. The second one is the number of impact (the number of contacting with any three of the four blocks in the instrument when the specimen is inflated). The difference of the number of impact in the failure and the first crack, and the impact toughness are also tested. The impact toughness is calculated as follows:

$$W = Nmgh \text{ (N} \cdot \text{m)} \tag{3.18}$$

where

W the impact toughness (N·m);
N the number of impact in the failure;
m quality of falling sphere (kg);
h the falling height of the impact hammer (m), 0.457 m;
g gravitational acceleration, $g = 9.81$ N/kg.

Bending Impact Test

The trabeculae (100 mm × 100 mm × 400 mm), the falling ball (3 kg) and the impact height (300 mm) are used in the test. The strain gages of residence in the maximum strain of test are applied and the strain changes in the process of the impact are observed. When the first crack occurs, the strain generates the mutation (with obvious creases). At this time, the number of the impact is that of the initial crack. The number of the cross-section impact is that of the failure impact when the crack penetrates the sample.

The work done by the impact is accumulated. That is, the energy (N·m) of the impact absorbed by the sample.

Influencing Factors of Impact Resistance

Factors include the performance of the concrete matrix, the fiber properties, the fiber content and the interface bonding.

3.3.1.6 Fatigue Strength Residence of Steel Fiber Reinforced Concrete

Test method: three point loading test.

Main Parameters:

- The characteristic value of load cycle: $\rho = \frac{P_{\min}}{P_{\max}}$

$\rho_{\min}$ the minimum load on the specimen;
$\rho_{\max}$ the maximum load on the specimen, the steel fiber reinforced concrete ($\rho = 0.1$); the sleeper ($\rho = 0.2$).

- The stress ratio: $n_s = \frac{f_{ftm}^f}{f_{ftm}}$

f_{ftm}^f the bending fatigue stress (strength) of steel fiber reinforced concrete;
f_{ftm} bending strength.

- The load frequency: the steel fiber reinforced concrete (1–10 Hz). When there is a low stress ratio, the frequency takes the upper limit. When there is a high stress ratio, the frequency takes the lower limit [6].

Flexural fatigue-resistant strength of steel fiber reinforced concrete: (f_{ftm}^f)

$$f_{ftm}^f = f_{ftm}\left(0.944 - 0.077\,\lg Ne + 0.12\lambda_f\right) \tag{3.19}$$

where

f_{ftm} the strength design value of steel fiber reinforced concrete (MPa);
Ne the cumulative times of the standard axle load in the period;
f_{ftm}^f the flexural fatigue-resistant strength of steel fiber reinforced concrete (MPa).

3.3.1.7 Elasticity and Toughness of Steel Fiber Reinforced Concrete

Elastic Modulus

It refers to the secant modulus when the stress is 40% of the axial compressive strength. The measure method is basically the same as the ordinary concrete. Its value is close to the value of the ordinary concrete.

Toughness

The toughness of steel fiber reinforced concrete is generally defined as the performance of absorbing the energy of steel fiber reinforced concrete or members. It is not affected by the load until the end of the destruction. It is usually expressed by the area surrounded by the stress—strain curve or load—deflection curve. It is also known as the degree of toughness. The method of using the degree of toughness as the toughness is called the energy method. The degree of toughness depends not only on the strength of the material, but also on the deformation of the material. The deformation capacity under the condition of maintaining a certain bearing capacity can also be used to evaluate the materials or structures of steel fiber reinforced concrete. It is commonly known as material or structural ductility. China's *The Test Methods of Steel Fiber Reinforced Concrete* (CECS13: 89) used the compressive toughness index and flexural toughness index as a toughness index to measure the steel fiber reinforced concrete.

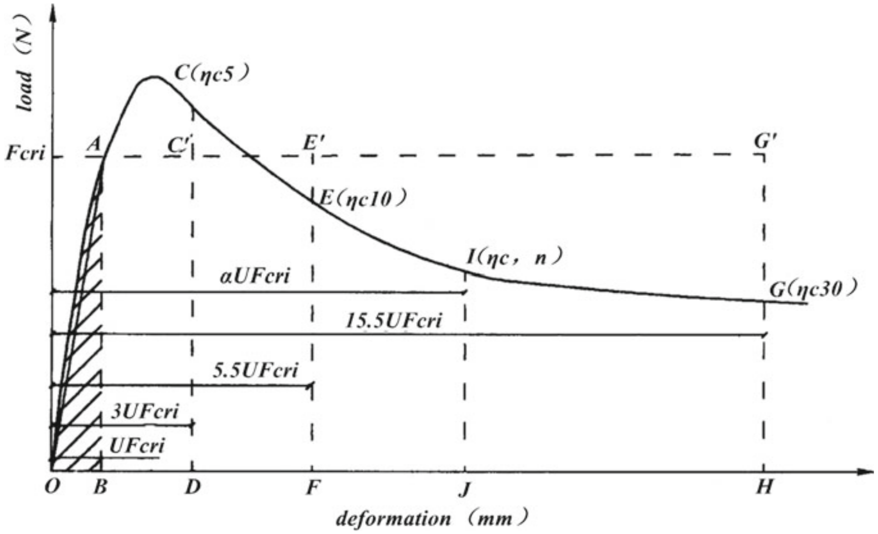

Fig. 3.2 Load-deformation curve and compressive toughness index $\eta_{c,n}\eta_{c5} = \frac{OACDarea}{OABarea}$,$\eta_{c10} = \frac{OAEFarea}{OABarea}$, $\eta_{c30} = \frac{OAGHarea}{OABarea}$. Reprinted from Ref. [4], copyright 2002, China Architecture and Building Press

Compressive Toughness Index

In the compressive load-deformation curve, the specimen of steel fiber reinforced concrete (see Fig. 3.2) was measured. The critical load F_{cri} is 0.85 time of the maximum load ($F_{cri} = 0.85F_{max}$). The corresponding abscissa is the critical deformation U_{Fcri}, The area *OAB* corresponding to the critical point (U_{Fcri}, F_{cri}) is the critical toughness. *D*, *F* and *H* points on abscissa are determined by the critical deformation of 3.0, 5.5 and 15.5 times. *OAB*, *OACD*, *OAEF* and *OAGH* are the critical toughness and the toughness of each given deformation. Therefore, the compressive toughness index for each given deformation is shown in Fig. 3.2.

For the load-deflection curve (shown in Fig. 3.2) of the ideal elastic-plastic material, the ductility index is $\eta_{c3} = 5$, $\eta_{c5.5} = 10$, $\eta_{c15.5} = 30$ respectively. Therefore, through comparing the toughness indices with the values of the ideal elastic-plastic material of steel fiber reinforced concrete under the corresponding deformation, the deviation of steel fiber reinforced concrete and the ideal elastic-plastic material can be determined.

The variation coefficient of the compressive load-carrying capacity of the specimen under given deformation αU_{Fcri} is calculated as follows:

$$\xi_{c,n,m} = \frac{\eta_{c,n,m} - \alpha}{\alpha - 1} \tag{3.20}$$

where

α the ratio of given deformation to critical deformation, according to *Test Method Standards Steel Fiber Reinforced Concrete*(CECS13: 89). The given α is 3.0,5.5,15.5. It can also be given according to test requirements;

η_{ca} the average compressive toughness index of a set of specimens corresponding to a given deformation ($\alpha \mathrm{U}_{Fcri}$).

The variation coefficient of load-carrying capacity of the ideal elastic-plastic material calculated from Eq. 3.22 is 1. Therefore, for steel fiber reinforced concrete, the change coefficient of load capacity ($\xi_{c,n,m}(<1)$) can be calculated according to given deformation ($\alpha \mathrm{U}_{Fcri}$) in the Eq. 3.20. $\xi_{c,n,m}$ is compared with 1 to assess its compressive toughness. The more $\xi_{c,n,m}$ is close to l, the more the steel fiber reinforced concrete is close to the ideal fiber-plastic material and the better the compressive toughness of the steel fiber reinforced concrete is.

Bending Toughness Index

The bending toughness is evaluated by the load-deflection curve obtained by the beam bending test of steel fiber reinforced concrete, the bending toughness index and the bearing-capacity variation coefficient. At the commonly used fiber volume ratio, the flexural toughness index of steel fiber reinforced concrete increases several times to dozens of times.

In the measured bending load—deflection curve of the steel fiber reinforced concrete, the initial crack point is determined by overlapping the ruler and linear part of the load—deflection curve to obtain the initial crack load (F_{cra}), the corresponding initial crack deflection ($W_{F_{cra}}$) and the initial cracking toughness. The toughness value, the bending toughness index, and the bending load-capacity change coefficient are corresponding to the initial crack deflection of 3.0, 5.5, 15.5 times respectively. They are calculated in the same way as the compressive toughness.

Measures of Improving the Reinforcing Effectiveness of Steel Fiber

- To improve the adhesion between the fiber surface and cement paste:

Such as machine used to change the cross-sectional shape of fiber, degreasing the fiber surface, roughening the surface, coating the surface, adding the extra material (silica fume) and so on.

- To promote the direction of the fiber which is relative to the direction of stress:

The shaking table or the flat-plate vibrator allows the fibers to be aligned in a plane, which is perpendicular to the direction of vibration or gravity. Therefore, the beam or plate is preferably cast in the horizon. The immersible vibrator should be tilted in the plane. It is better to vibrate when there is a 30° angle with the pouring plane.

- To determine the ideal V_f and l_f/d_f:

Both compactness and advantages of improving V_f and l_f/d_f are considered. The characteristic parameters of the fiber content ($\lambda_f = V_f l_f/d_f$) reflect the combined effect. A reasonable value is determined in the design.

3.3.2 Shrinkage and Creep

Shrinkage

The shrinkage value of steel fiber reinforced concrete decreases with increase of V_f.

The shrinkage-restraining effect on the high-strength concrete is more significant. The shrinkage-restraining capacity of fiber shapes: wavy fiber > hook fiber > straight and square fibers. The aggregate has a limited effect on shrinkage, but it is limited by the shape and scale of aggregate. The shrinkage-restraining effect is limited while the shrinkage value of steel fiber reinforced concrete decreases with increase of V_f.

Creep due to the binding effect of steel fiber, the creep of steel fiber reinforced concrete is less than that of ordinary concrete.

3.3.3 Durability of Steel Fiber Reinforced Concrete

3.3.3.1 Chloride Ion Corrosion Resistance

The corrosion resistance improves because the key of steel fiber reinforced concrete impacting on the chloride ion corrosion resistance is the crack width. With the increase of the crack width, the concentration of chloride ion at the crack increases. When the cleavage width is more than 0.5 mm, the effect on the diffusion of chloride ion is very great. When the crack width is less than 0.2 mm, the effect on chloride ion diffusion is very small. The incorporation of steel fibers inhibits the initiation of cracks during the formation of the structure, further refining the scale of the cracks and reducing the number of the original cracks. From this point of view, the impermeability improves.

3.3.3.2 Frost Resistance

The frosting process: when the swelling pressure is greater than the concrete tensile strength, the internal cracking, the surface flaking, the accelerated damage of concrete are caused till the damage. Therefore, it mainly needs to reduce the water-cement ratio (W/C), the freezing point of water in concrete, and improve the compactness, the impermeability of concrete and the pore structure if it wants to reduce the damage process of concrete freezing fatigue. In addition, in the process of structure-forming and freezing, it needs to improve the ability of crack resistance and swelling resistance. The steel fiber plays this role. Thus, the frost resistance of concrete improves.

3.3.3.3 Other Durability

The steel fiber can improve the abrasion resistance and fire resistance.

3.4 Design and Construction Technology of Mix Proportion of Steel Fiber Reinforced Concrete

3.4.1 Design of Mix Proportion of Steel Fiber Reinforced Concrete

3.4.1.1 Design Characteristics of Mix Proportion of Steel Fiber Reinforced Concrete

Compared with the ordinary concrete, in addition to meet the strength, workability and durability, there are following characteristics.

- Strength meets two indices. That is, compressive strength and bending strength or tensile strength. The water-cement ratio (W/C) is calculated according to the compressive strength. The volume ratio of steel fiber (V_f) is calculated according to the tensile or bending strength.
- Work evaluation (V_b(s)) or t slump.
- The selection of steel fiber reinforced concrete and matrix strength grade is different from the ordinary concrete.

General requirements: ≥C30; $d_{\max} \geq 20$ mm; high sand ratio. The requirements for the high-strength concrete may be appropriately smaller.

3.4.1.2 Mix Proportion of Steel Fiber Reinforced Concrete of Pavement

Economy should be considered in the design of mix proportion of steel fiber reinforced concrete. At the same time, the following three technical requirements should also be met [9].

Bending Strength

The standard value of 28 d design bending strength (f_{rf}) of steel fiber reinforced concrete should conform with the design specifications.

The mean of 28 d bending strength of steel fiber reinforced concrete should be calculated according to Eq. 3.21.

$$f_{cf} = \frac{f_{rf}}{1 - 1.04c_v} + ts \tag{3.21}$$

where

f_{cf} the mean of 28 d bending strength of steel fiber reinforced concrete (MPa);
f_{rf} the standard value of bending strength of steel fiber reinforced concrete (MPa);
s the standard deviation (MPa) of the tensile strength of specimen;
t the assurance coefficient determined by Table 3.5;

c_v the variation coefficient of the bending strength determined by the range of statistical data in the Table 3.6.

Workability

The slump of steel fiber reinforced concrete can be 200 mm smaller than the specified value in Tables 3.7 or 3.8.

The unit water consumption can primarily be selected in Table 3.9 when the steel fiber reinforced concrete is mixed with superplasticizer. It is then determined by the slump measured by the mixture.

Table 3.7 is suitable for slipform paver with over-lay angle. For the slipform paver with no over-lay angle, the optimum coefficient of vibration viscosity is 250–600 N s/m^2. The best slump for the concrete with pebble is 10–40 mm, while for the concrete with gravel it is 10–30 mm.

The maximum unit water consumption of pebble concrete in slipform paving should not be larger than 155 kg/m^3. The maximum unit water consumption of gravel concrete should not be larger than 160 kg/m^3.

When broken pebble is used, the median of gravel and pebble is adopted as the maximum unit water consumption.

When the volume ratio of steel fiber increases or decreases by 0.5%, the unit water consumption will accordingly increase or decrease by 8 kg/m^3;

Table 3.5 Coefficient of assuring rate (t)

Highway technical rates	Discrimination probability P	Number of specimen n (group)				
		3	6	9	15	20
Freeway	0.05	1.36	0.79	0.61	0.45	0.39
First class highway	0.10	0.95	0.59	0.46	0.35	0.30
Second class highway	0.15	0.72	0.46	0.37	0.28	0.24
Third and fourth class highway	0.20	0.56	0.37	0.29	0.22	0.19

Table 3.6 Flexural-tensile strength coefficient of variability of concrete pavement of highways

Highway technical rates	Freeway	First class highway		Second class highway	Third and fourth class highway	
Variability levels of flexural-tensile strength of concrete	Low	Low	Low	Middle	Middle	High
Flexural-tensile strength coefficient of variability (c_v)	0.05–0.10	0.05–0.10	0.10–0.15	0.10–0.15	0.10–0.15	0.15–0.20

Table 3.7 Optimum workability and allowable range of slipform paving for concrete pavement

Index boundary	Slump S_L(mm)		Vibration viscosity coefficient η(N s/m^2)
	Pebble concrete	Gravel concrete	
Optimum workability	20–40	25–50	200–500
Allowable fluctuating range	5–55	10–65	100–600

Note The suitable paving speed of slipform paver should be controlled at 0.5–2.0 m/min

Table 3.8 Slump and maximum unit water consumption of concrete in different ways of pavement construction

Paving ways	Track paving		Triaxial paving		Small machine paving	
Pumping slump (mm)	40–60		30–50		10–40	
Paving slump (mm)	20–40		10–30		0–20	
Maximum unit water consumption (kg/m^3)	Gravel 156	Pebble 153	Gravel 153	Pebble 148	Gravel 150	Pebble 145

Note The maximum unit water consumption in the table is the value of air-dried state of medium sand, coarse and fine aggregates. When fine sand is used, the high effective water reducer should be used

Table 3.9 Selection table of unit water consumption of steel fiber reinforced concrete

Mixture conditions	Types of coarse aggregate	Maximum nominal diameter of coarse aggregate D_m (mm)	Unit water consumption (kg/m^3)
Aspect ratio $L_f/d_f = 50$ $\rho_f = 0.6\%$ Slump 20 mm Medium sand, fineness modulus 2.5 Water-cement ratio 0.42–0.50	Gravel	9.5, 16.0	215
		19.0, 26.5	200
	Pebble	9.5, 16.0	208
		19.0, 26.5	190

Note When the aspect ratio of steel fiber increases or decreases by 10, the unit water consumption will accordingly increase or decrease 10 kg/m^3

The slump ranges from 5 to 10 mm. The slump of 20 mm increases or decreases by 10 mm, the unit water consumption will accordingly increase or decrease 7 kg/m^3;

The fineness modulus ranges from 2.0 to 3.5. The fineness modulus of sand increases or decreases by 0.1, the unit water consumption will accordingly increase or decrease 1 kg/m^3.

Table 3.10 Maximum water-cement (binder) ratio and minimum unit cement consumption of steel fiber reinforced concrete which meets the requirement of durability

Grades of highway		Freeway, first class highway	Second class highway	Third and fourth class highways
Water-cement (binder) ratio		0.47	0.49	0.50
Water-cement (binder) ratio required by frost resistance		0.45	0.46	0.48
Water-cement (binder) ratio required by deicer-scaling resistance		0.42	0.43	0.46
Minimum unit cement consumption (kg/m^3)	Grade 42.5	360	360	350
	Grade 32.5	370	370	365
Minimum unit cement consumption required by frost resistance and deicer-scaling resistance (kg/m^3)	Grade 42.5	380	380	375
	Grade 32.5	390	390	385
Minimum unit cement consumption mixed with fly ash (kg/m^3)	Grade 42.5	320	320	315
	Grade 32.5	340	340	335
Minimum unit cement consumption mixed with fly ash required by frost resistance and deicer-scaling resistance (Grade 42.5) [kg/m^3]		330	330	325

Durability

The maximum water-ash(glue) ratio and the minimum unit cement consumption which meet the durability of steel fiber reinforced concrete should be conform with the specifications in Table 3.10.

The sea water and sea sand is strictly prohibited in the steel fiber reinforced concrete. The chloride and its hardening accelerator, anti-freezing agent and other addictives should not be mixed.

The pavement in the sea wind, acid rain, sulfate and deicing salt and other environments should be mixed with fly ash of grade I and II in the *Specifications*. The bridge should be mixed with silica fume and ground slag of grade S95 and S105.

Design steps of Mix Proportion of Steel Fiber Reinforced Concrete

Calculation of Bending Strength of Concrete (f_{cf})

Calculation and Determination of Water-Cement (Glue) Ratio

According to the type of coarse aggregate, the water-cement ratio can be calculated according to the following statistical formula.

Gravel or crushed stone concrete:

$$\frac{W}{C} = \frac{1.5684}{f_{cf} + 1.0097 - 0.3595 f_s} \tag{3.22}$$

Pebble concrete:

$$\frac{W}{C} = \frac{1.2618}{f_{cf} + 1.5492 - 0.4709 f_s} \tag{3.23}$$

where

$\frac{W}{C}$ the water-cement ratio;
f_s 28 d tensile strength of cement (MPa).

When it is mixed with fly ash, the amount of fly ash that substitutes the cement should be included in the excess substitution method (the amount of fly ash that substitutes the sand is not included). The water-glue ratio ($\frac{W}{C+F}$) substitutes the water-cement ratio ($\frac{W}{C}$).

The minimum value should be obtained in the water-cement (glue) ratio which meets the calculated value and the durability of the bending strength (Table 3.10).

The volume rate of steel fiber content should be primarily selected in the range of 0.60–1.0%. When the thickness reduction coefficient is small, the volume ratio takes the upper limit. When the aspect ratio is big, the volume ratio takes the lower limit. The anchored end should also take the lower limit.

Check the Table 3.9 and primarily select the unit water consumption.

The unit cement consumption of steel fiber reinforced concrete should be calculated according to Eq. 3.24.

$$C_{of} = \left(\frac{C}{W}\right) W_{of} \tag{3.24}$$

where

C_{of} the unit cement consumption of steel fiber reinforced concrete (kg/m^3);
W_{of} the unit water consumption of steel fiber reinforced concrete (kg/m^3).

The sand ratio of steel fiber reinforced concrete can be calculated according to Eq. 3.25. It also can be primarily selected according to Table 3.10. It should range from 38 to 50%.

$$S_{pf} = S_p + 10\rho_f \tag{3.25}$$

where

S_{pf} the sand ratio of steel fiber reinforced concrete (%);
ρ_f the volume ratio of steel fiber (%).

The amount of sand material can be calculated by the density method or the volume method. According to the density method, the unit mass of steel fiber reinforced concrete is 2450–2580 kg/m^3. According to the volume method, the gas content of design should be included.

The orthogonal test method should be used to optimize the mix proportion for steel fiber reinforced concrete in the important pavement and bridge engineering.

Example: In a secondary highway of cold mining area, the design strength of steel fiber reinforced concrete should be grade CF30. The standard value of bending strength of steel fiber reinforced concrete is 5.5 MPa. The slump is 20–40 mm. The shear steel fiber is used and its aspect ratio is 60. The ordinary Portland cement of grade 32.5 is used. The measured bending strength is 7.0 MPa and its density is 3.1 g/cm^3. The fine aggregate is medium sand. Its fineness modulus is 2.50 and its apparent density is 2.65 g/cm^3. The coarse aggregate is gravel. Its nominal particle size is 19.0 mm and its apparent density is 2.70 g/cm^3. The standard deviation of bending strength is 0.5 MPa ($n = 9$). Try to design the primary mix proportion of the steel fiber reinforced concrete. The steel fiber density is 7.8 g/cm^3. The water-cement ratio required by the durability is not more than 0.46. The air-entraining addictive is added and its air-entraining content is 5.0%.

The design steps are as follows:

- Calculate the bending strength of steel fiber reinforced concrete according to Eq. 3.26

$$f_{cf} = \frac{f_{rf}}{1 - 1.04c_v} + ts \tag{3.26}$$

where $f_{rf} = 5.5$ MPa, $S = 0.5$ MPa. The variation level of the secondary highway is medium. The value of c_v is 0.13. According to $n = 9$ and $t = 0.37$,

$$f_{cf} = \frac{5.5}{1 - 1.04 \times 0.13} + 0.37 \times 0.5 = 6.54\ (\text{MPa})$$

- Determine the water-cement ratio:

Calculate water-cement ratio according to Eq. 3.22

Table 3.11 Selection values of sand ratio of steel fiber reinforced concrete (%)

Mixing conditions	Gravel with the maximum nominal size of 19 mm	Pebble with the maximum nominal size of 19 mm
$L_f/d_f = 50$; $\rho_f = 1.0\%$ $W/C = 0.5$; Fineness modulus of sand $M_x = 2.5$	45	40
L_f/d_f increases or decreases by 10	±5	±3
ρ_f increases or decreases by 0.10%	±2	±2
W/C increases or decreases by 0.1	±2	±2
Fineness modulus of sand M_x increases or decreases by 0.1	±1	±1

$$\frac{W}{C} = \frac{1.5684}{f_{cf} + 1.0097 - 0.3595 f_s} = \frac{1.5684}{6.54 + 1.0097 - 0.3595 \times 7.0} = 0.32$$

The water-cement ratio required by the durability: W/C = 0.46 (Table 3.10) so the water-cement ratio in the engineering is 0.32;

- The primarily selected volume ratio of steel fiber is 0.8%. Then the unit volume consumption of steel fiber is calculated as follows: $F_o = 0.8\% \times 1{\times}7800 = 62.4\ \text{kg/m}^3$.
- The primarily selected unit water consumption: $W_{of} = 200\ \text{kg/m}^3$ (Table 3.9). After the adjustment, $W_{of} = 233\ \text{kg/m}^3$.
- Calculate the unit cement consumption.

$$C_{of} = \left(\frac{C}{W}\right) W_{of} = \left(\frac{1}{0.32}\right) \times 233 = 728\ \text{kg/m}^3$$

When $C_{of} = 500\ \text{kg/m}^3$, $W_{of} = C_{of} \times \left(\frac{W}{C}\right) = 500 \times 0.32 = 160\ \text{kg/m}^3$ ($\because C_{of} > 500\ \text{kg/m}^3$).

- Sand rate: $S_{pf} = 45$ (Table 3.11).
- Calculate the sand consumption:

$$\begin{cases} \frac{C_{of}}{\rho_c} + \frac{F_o}{\rho_f} + \frac{W_{of}}{\rho_w} + \frac{S_{of}}{\rho_{os}} + \frac{G_{of}}{\rho_{og}} + 10 \times \alpha = 1000 \\ S_{pf} = \frac{S_{of}}{S_{of} + G_{of}} \times 100 \end{cases}$$

According to the above formula:

$$S_{of} = 748\ \text{kg/m}^3$$

$$G_{of} = 914\ \text{kg/m}^3$$

- Determine the mix proportion (omitted).

3.4.2 Preparation Process of Steel Fiber Reinforced Concrete

The uniformity and compactness of steel fiber reinforced concrete should be ensured in the process as much as possible. To avoid clustering, factors which cause to cluster are as follows: Before mixing with the concrete, the fiber has clustered and cannot disperse; the fiber permeates too fast so that the ball has been formed; the fiber content is too high, the mixing power is insufficient, and before the fiber disperses, add water and so on.

3.4.2.1 Mixing Process

- The forced mixer should is commonly used. When the consistency is large, each mixing amount should not be more than 80% of the rated mixing amount.
- Feeding order and method.

Dry-mixed and then wet-mixed in the process. The solid components such as steel fiber, coarse aggregate, fine aggregate and cement are dry-mixed so that the steel fiber is evenly dispersed into the solid components. Then they are wet-mixed with water added so that the steel fiber is evenly dispersed in the concrete.

The wet-mixed process. The key is the order of feeding in the wet-mixed process. The coarse aggregate, fine aggregate and cement are dry-mixed. Then they are wet-mixed with water added. At the same time, a fiber disperser is used to evenly feed components and the mixing continues. Mechanically dispersed fibers must be used in this process.

The staged charging process. 50% fine aggregate and coarse aggregate, and all steel fiber are dry-mixed evenly. Then the rest 50% coarse aggregate and fine aggregate, all cement and water are wet-mixed to achieve the uniform purpose. It is more suitable to use a freely falling mixer. But the mixing time must be relatively extended.

3.4.2.2 Transport, Pouring and Maintenance

Transport

The vibration generated in the transportation causes the steel fiber to sink and causes the mixture to segregate, which thereby affects the homogeneity of the mixture. Therefore, the transport time and distance should be shortened or the transport equipment with the mixer should be used.

Pouring

The flat vibration can promote the steel fiber from the three-dimensional chaos to two-dimensional chaos so as to improve the effective coefficient (η_θ) of the fiber direction. The immersible vibrator should not be inserted into the concrete mixture in the perpendicular direction of structural strength. In order to avoid the orientation distribution of steel fiber along the vibrator, the effective coefficient in the fiber direction is reduced. Generally, it is required to obliquely insert and the angle with the plane is not more than 30°. The vibration time should not be too long because the high density of fiber will cause to sink.

The vibrating and leveling process with steel fiber reinforced concrete in the pavement, airport runway and deck:

- to vibrate densely with the flat vibrator and then vibrate flat with the vibration beam;
- to roll the surface flat with the ribbed metal rolling. When the surface of steel fiber reinforced concrete does not bleed, smooth it with a metal knife. The bare fiber and floating slurry are not used.
- to do the broom finish before the initial set. The brush and roll can be used to do the broom finish. The wood scraper, coarse brush and bamboo broom must not be used so as not to bring steel fiber into the concrete.

Maintenance: the early strength of steel fiber reinforced concrete is high so it should strengthen the early wet maintenance.

3.5 Application of Steel Fiber Reinforced Concrete in Engineering

3.5.1 Steel Fiber Reinforced Concrete Pavement

Defects of ordinary concrete pavement: high thickness, various materials, low crack resistance, low anti-shrinkage, low anti-peeling and wear resistance.

The steel fiber reinforced concrete pavement can overcome certain shortcomings. It is mainly used in the restricted road of elevation, toll stations, the concrete overlay and deck pavement, expansion joints or bridge telescopic devices on both sides [8].

3.5.2 Bridge Structure and Rail Sleeper

It is used in the bridge deck pavement and the local reinforcement of bridge deck joints. It can also be used in the bridge structure. For example, 1.0% steel fiber reinforced concrete was used in the rib arch of Zhuxi River Bridge in Dazu County, Sichuan Province. The arch ring size was reduced and the cost reduced by 11%. The rail joints and the corner of small radius of curvature (radius of curvature < 350 m) in the railway are complex. The pre-stress concrete sleepers often fail prematurely so they can be replaced with wooden sleepers. However, the wood is perishable so that the steel fiber reinforced concrete is used. In addition, it is used in the waterproof protective layer of railway bridge deck and other engineering. It improves the carrying capacity and the crack resistance.

3.5.3 Building Structure and Products

The aseismic structure: 1.5% steel substitutes 1.7% hoop (volume ratio). It makes the shear strength and the energy consumption increase by 27 and 28% respectively. It can also avoid crowded joints.

The explosion-proof structure and the local reinforcement (such as beam hangers), the building wall panels and roof, the thin wall water storage structure, the centrifuge tube, sewage wells and other refractory concrete and refractory products (such as: industrial furnace door, lintel).

3.5.4 Hydraulic Buildings, Ports and Marine Engineering

3.5.4.1 Hydraulic Buildings

It is used to improve the anti-seepage and the crack resistance of the dam surface, and the high-speed water flow, such as spillway, drain hole, pressure waterway, stilling pool, floodgate soleplate and so on. But the anti-erosive and anti-abrasive performance need improving.

3.5.4.2 Ports and Marine Engineering

Japan: steel fiber reinforced concrete is used as the pile coating of steel pipe. After 10-year seawater immersion, it is still intact.

Norway: it is used in oil extraction platforms and other structures.

China: the berthing structure was repaired by steel fiber reinforced concrete at Banshengdong Dock in Zhejiang Province. The effect is very good.

3.5.5 Tunnel Lining and Slope Protection

In the engineering, such as the tunnel lining and slope protection, the steel fiber reinforced concrete is generally used to spray construction instead of the steel reinforced concrete lining, slope protection or steel mesh reinforced shotcrete.

Compared with the plain shotcrete, the steel fiber reinforced shotcrete (“steel shotcrete” for short) have many advantages: higher tensile strength, higher bending strength and shear strength; higher shock resistance and aseismic capacity; better toughness; better freezing resistance, heat resistance and fatigue resistance; stronger crack resistance; lower rebound rate aggregate.

Because of the above characteristics of steel fiber reinforced shotcrete, it has been successfully applied in the tunnel design and construction of New Austrian Tunnel Method. In the construction of shotcrete, the rebound of the material is inevitable, but the rebound is different in the sprayer performance, the forming performance of spraying materials, the technical levels of constructors and the rebound amount.

In the rebound aggregate, the rebound rate is much bigger than that of the aggregate. In other words, the proportion of materials in the aggregate has changed a lot from the spraying proportion to the structure proportion, especially the coarse aggregate and steel fiber. It should be given full consideration in the design.

Exercises

1. What characteristics are there on the interface between the steel fiber and cement base? Give 2–3 specific measures to improve the interface.
2. Briefly describe the measures to improve the reinforcing effectiveness of steel fiber.
3. Briefly describe the design process of steel fiber reinforced concrete pavement.
4. Briefly describe the factors that cause steel fiber to cluster.
5. The steel fiber volume ratio of steel fiber reinforced concrete is 2%. The steel fiber density is 7.8 g/cm^3. How many kilograms of steel fiber should be added in the steel fiber reinforced concrete per cubic meter?
6. The bending strength of concrete base is 5.5 MPa. The sheared steel fiber is used. Its aspect ratio is 60 and fiber volume ratio is 2%. The impact coefficient of bending strength of steel fiber is 0.73. Try to calculate the bending strength of steel fiber reinforced concrete.
7. The W/C of concrete is 0.45. The compressive strength of cement is 52.5 MPa. The design value of bending strength of steel fiber reinforced concrete is 5.5 MPa. What is the volume ratio of sheared steel fiber with the aspect ratio of 60? The strength guarantee rate is 95%, the standard deviation of bending strength is 0.65 MPa.

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Chapter 4
Modified Asphalt and Material Requirements for SMA

4.1 Modified Asphalt

4.1.1 Concept and Classification of Modified Asphalt

4.1.1.1 Concept of Modified Asphalt

In accordance with the definition of *Technical Specification for Construction of Highway Asphalt Pavements* (JTJ 032-94) and *Technical Specification for Construction of Highway Modified Asphalt Pavements* (JTJ 036-98), the modified asphalt, including modified asphalt mixture, is made from addictives (modifiers) such as rubber, resin, polymer, rubber powder or other fillers, or taking some measures such as taking mild oxidation of asphalt to improve the properties of asphalt [1, 2].

Addictives (modifiers) refer to materials of improving the performance of asphalt pavement which are made by adding a natural or artificial organic or inorganic material to the asphalt or asphalt mixture which can be melted and dispersed in the asphalt to react with the asphalt or cover on the aggregate surface.

4.1.1.2 Classification of Modified Asphalt

According to Technological Purposes and Mixture of Modified Asphalt

To add modifiers: improve the mechanical characteristic (high-temperature stability, fatigue resistance, and low-temperature crack resistance), the adhesion, and the aging resistance.

To modify the asphalt physically: add mineral fillers (carbon black, sulfur, asbestos, and cellulose fiber), the glass fiber grille, the plastic grille, the geotextile, and the waste rubber powder.

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https://doi.org/10.1007/978-981-13-6068-8_4

To blend asphalt: add natural asphalts such as lake asphalt, rock asphalt, and submarine asphalt.

The asphalt process: semi-oxidized asphalt, foam asphalt, etc.

According to the Polymer for Asphalt Modification on the Road

There are many types of polymers for modification, generally divided into three categories as follows:

Rubber/Elastomer

There is commonly used Natural Rubber (NR), Styrene–Butadiene Rubber (SBR), Chloroprene Rubber (CR), Butadiene Rubber (BR), Ethylene–Propylene–Diene—Monomer (EPDM), Isoprene Rubber (IR), Acrylonitrile-Butadiene Rubber (ABR), Isobutylene–Isoprene Rubber (IIR), Styrene–Isoprene Rubber (SIR), Silicone Rubber (SR), and Fluorine Rubber (FR). Among them, SBR has the main characteristics of high-temperature stability, high elasticity, high mechanical strength, and high adhesion. CR has the polarity, and is often used in coal asphalt.

Thermoplastic Rubber/Elastomer

There is mainly Styrene–Butadiene–Styrene block copolymer (SBS), Styrene–Isoprene–Styrene block copolymer (SIS), and Styrene–Polyethylene/Butyl-Polyethylene block copolymer (SE/BS). SBS is a thermoplastic styrene–butadiene rubber prepared by the cationic polymerization. There are two kinds of SBS, including linear SBS and radical SBS. The modification effect of radical SBS is better than that of the linear SBS. SBS has good deformation self-recovery and fracture self-healing. It has become the most commonly used road asphalt modifier.

Thermoplastic Resin

There are commonly used thermoplastic resins such as Polyethylene (PE), Ethylene-Vinyl Acetate (EVA) copolymer, Random Polypropylene (APP), Polyvinyl Chloride (PVC), and polyamide. There are thermosetting resins such as epoxy resin. PE is a high-pressure low-density polyethylene, which is compatible with domestic high paraffin content asphalt. It cannot only improve the high-temperature stability of asphalt, but also improve the low-temperature brittleness. It is cheap and widely used in China. The elasticity of EVA is similar to that of rubber but the antiaging characteristic of EVA is better. The density and melting index of EVA are close to those of low-density polyethylene but the characteristics of EVA such as flexibility, toughness, crack resistance, antiaging, and anti-light are better. EVA has good thermal stability, good oxidation stability, wide rubber temperature range, good low-temperature resistance, and strong water resistance.

4.1.1.3 Several Major Modified Asphalts

SBS-Modified Asphalt

Main features of SBS-modified asphalt are given below:

After the temperature is higher than 160 °C, the viscosity of modified asphalt is basically similar to that of the original asphalt. It can be mixed to use like ordinary asphalt.

After the temperature is lower than 90 °C, the viscosity of the modified asphalt is several times more than that of the original asphalt. The high-temperature stability of modified asphalt is good so that the anti-rutting ability of modified asphalt mixture pavement greatly improves.

The low-temperature elongation and brittle point of modified asphalt have obviously improved compared with the original asphalt. So the low-temperature crack resistance and fatigue life of modified asphalt mixture are obviously improved.

PE-Modified Asphalt

The high-temperature stability, the adhesion with aggregate; the temperature susceptibility, and the aging resistance of PE-modified asphalt are improved, but the ductility at normal temperature (25 °C) is reduced.

SBR-Modified Asphalt

The thermal stability, ductility, and adhesion of SBR-modified asphalt have improved compared with the original asphalt. The heat aging performance has also improved.

EVA-Modified Asphalt

The thermal stability of EVA-modified asphalt has improved but the durability has not changed too much.

4.1.1.4 Modified Asphalt and Its Pavement Performance

With the increasing traffic volume, the proportion of large-scale vehicles and overloaded vehicles is increasing. So the traffic demand for pavement is more and more increasing. The pavement performance of modified asphalt mainly refers to [3] the following:

- High-temperature anti-rutting performance, that is, the capacity to resist shear deformation;
- Low-temperature crack resistance performance, that is, the capacity to resist crack by the low-temperature shrinkage;
- Water stability, that is, the capacity to resist the damages of asphalt mixture which causes asphalt film to strip, drop, loose, and pit;

- Fatigue resistance performance, that is, the capacity to resist the destruction of pavement asphalt mixture under the repeated load (including traffic and temperature load);
- Antiaging performance, that is, the capacity to resist the brittle asphalt mixture impacted by climate which causes to lose adhesion and other good performances;
- Surface service performance, including low-noise and anti-skid performance under the conditions of humidity, preventing splashing water, and water mist on the back of car in the rain. The performance directly affects the traffic safety and environmental protection;
- Driving comfort performance mainly refers to the traffic bumps generated by the roughness, including horizontal flatness.

The water stability, fatigue resistance, and antiaging performance are generally called the durability. In addition to the above properties, the pavement performance of asphalt mixture should also include construction performance.

4.1.2 Evaluation Methods of China's Modified Asphalt Technical Index

4.1.2.1 Evaluation Methods of Modified Asphalt Technical Index

The indicators of characteristics of traditional asphalt are not suitable for the evaluation of polymer-modified asphalt index. That is, the classic index of evaluating asphalt performance cannot explain the nature of polymer-modified asphalt. Therefore, according to the actual situation of China, three methods which adapt to China are developed to evaluate the properties of modified asphalt.

The change in the index value of modified asphalt performance is used to measure penetration, softening point, ductility, viscosity, and brittle point. The greater the change value is, the better the modified effect is. The method is simple and the meaning is clear. So, it is the most commonly used method in engineering practice.

The test methods were developed according to the characteristics of modified asphalt, such as elastic recovery test, force ductility test, toughness and tenacity test, impact plate test, and segregation test.

Asphalt binder performance specifications were proposed by USA Strategic Highway Research Program (SHRP).

Test Methods of Modified Asphalt Technical Index

Elastic Recovery (Rebound) Test

The elastic recovery ability of asphalt is strong so that the road surface under the action of deformation can quickly recover after the load. Thus, the residual deformation is small. The test mold is similar to the mold in ductility test (the tensile test in the ASTM D6084-97), but the side in middle section of mold is replaced by a linear side mold,

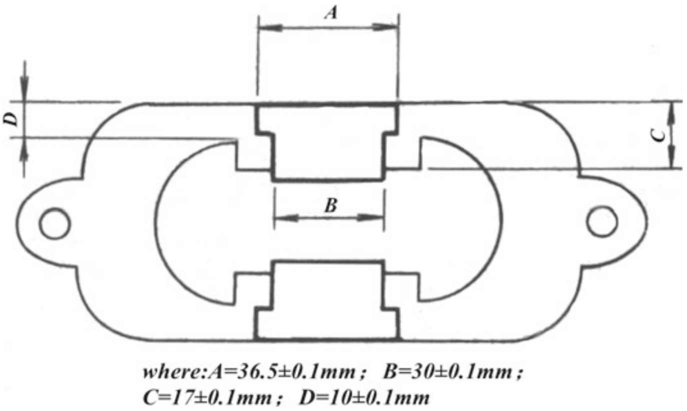

Fig. 4.1 Linear ductility test mode for elastic recovery test. Reprinted from Ref. [4], copyright 2002, China Architecture and Building Press

as shown in Fig. 4.1. The ductility test method is carried out at the test temperature of 25 ± 0.5 °C. After stretching for 10 cm at the required rate of 5 cm/min, the specimen stopped. The asphalt specimen was cut into two parts with scissors in the middle. Keep the specimen in the water for 1 h and then make the tips of two half-specimen contact. The length of specimen was measured as X. According to Eq. (4.1), calculate the elastic recovery, that is, the percentage of recovery deformation after the 10 cm elongation in the ductility test.

$$\text{Recovery rate} = \frac{10 - X}{10} \times 100 \tag{4.1}$$

Toughness and Tenacity Test

The toughness and tenacity tests of asphalt are to measure the toughness and tenacity of asphalt with metal hemisphere at the specified high temperature with high-speed elongation. In general, the test temperature is 25 °C and the tensile speed is 500 mm/min. The radius of tensile hemisphere is 11.1 mm. The container of specimen is similar to the penetration box, as shown in Fig. 4.2.

The main steps of test are as follows:

- Pour 50 g hot asphalt into a specimen container preheated at 80 °C.
- Put the tensile hemisphere head into the asphalt, and the positioning bracket above the specimen container to maintain the height of hemisphere head the same as the upper surface of asphalt. Then, put it into tank insulation for 1–1.5 h at 25 °C constant temperature.
- Install the tester and the sampler into the upper and lower indenter fixtures of tensile tester.
- After adjusting the recorder and the tester, start stretching at 500 mm/min and end at 300 mm. At this time, the recorder records the load and the drawing time, as

Fig. 4.2 Tensile conditions of toughness and tenacity test. Reprinted from Ref. [5], copyright 2002, China Architecture and Building Press

shown in Fig. 4.3. Y-axis represents the load and X-axis represents the deformation in the recorder. The test procedure requires that the toughness and ductility tester must be removed from the thermostat tank 1 min later because the test time cannot exceed 1 min. On the load-deflection curve of Fig. 4.3, the falling straight-line portion of curve BC is extended to point E indicated by the dotted line. The area A_1 and A_2 surrounded by the curve $ABCE$ and $CDFE$ are, respectively, measured. The toughness (T_0) is $A_1 + A_2$ and the tenacity (Te) is A_2.

Force Ductility Test

The device for force ductility test is that a conventional ductile tester is attached with a load cell. The test mode is the same strip mode as the tensile test. The test temperature is usually 5 °C and the tensile speed is 5 cm/min. The maximum load of sensor can be 1 kN. The test results are recorded by the X–Y function recorder. The recorded tension–deformation (ductility) curve is shown in Fig. 4.4. The figure shows the peak load of modified asphalt test curve and the area of tension–deformation curve. Generally, the brittler the asphalt is at low temperature, the smaller the ductility is. But the greater the peak force is, the smaller the overall area of tension–deformation curve of toughness is. It is important for evaluating the performance of modified asphalt to study the shape and area of this curve.

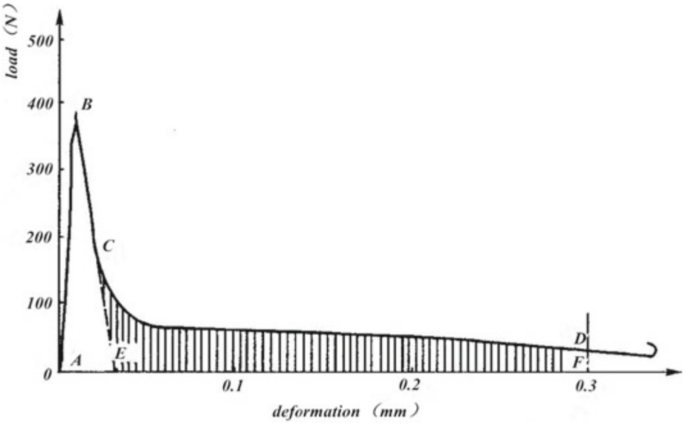

Fig. 4.3 Load–deformation curve of toughness and tenacity test. Reprinted from Ref. [5], copyright 2003, China Communications Press

Segregation Test

As the polymer is segregated from the asphalt in the process of stopping mixing, cooling, and storage, the polymer-modified asphalt cannot be used immediately after producing. It needs to cool, store, transport, and reuse after heating. The segregation test of modified asphalt is carried out to evaluate the compatibility of modifier with the matrix asphalt.

The polymer-modified asphalts such as SBR and SBS float when segregating. The test is to inject asphalt in the test tube and the specimen height is 180 mm. The specimen is then put in oven for 48 ± 1 h at 163 ± 5 °C. is removed and put

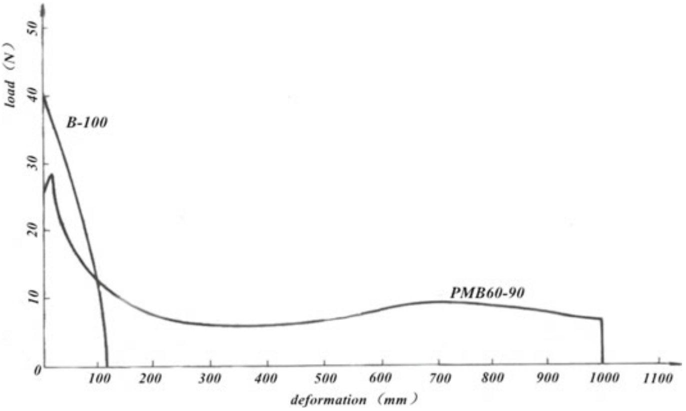

Fig. 4.4 Tension–deformation (ductility) curve of force ductility. Reprinted from Ref. [5], copyright 2003, China Communications Press

Table 4.1 Test evaluation of PE and EVA

Record	Report	Record	Report
Uniform, no crust, and sediment	Uniform	Crust of thick polymer on whole surface (>0.8 mm)	Thick crust completely
Thin polymer crust at the edge of cup	Thin crust at the edge	No crust on the surface but thin sediment at the bottom of container	Thin sediment at the bottom
Thin polymer crust on whole surface	Thin crust completely	No crust on the surface but thick sediment at the bottom of container (>0.635 cm)	Thick sediment at the bottom

in the refrigerator for 1 h later. The modified asphalt condenses into a solid and then is pulled out. It is cut into the same three parts. The softening point of top and bottom specimens is measured, respectively. The difference of their softening points indicates the degree of segregation.

The polymer-modified asphalts, such as PE and EVA, adsorb the four sides of the container wall when segregating. Because of the surface crusts, the segregation test is to pour the asphalt into the specimen cup at the high temperature. Then, put it into oven for 15–18 h at 135 °C and observe the surface. At the same time, slowly detect the specimen with a small scraper, and check the consistency of surface layer and the sediment of the bottom, as shown in Table 4.1.

Plate Impact Test

The test is used to evaluate the low-temperature adhesion of modified asphalt and stone, as shown in Fig. 4.5. 40 g asphalt is poured into a 200 mm × 200 mm × 20 mm steel plate (the edge with a 5 mm high fence). The asphalt thickness is 1 mm. 10 rows of 4.75–9.5 mm dry clean gravels are evenly placed on the asphalt surface. There are 10 in each row and 100 in total. After cooled at room temperature, it is put into the oven at 60 °C for 5 h so that gravels can adhere to asphalt well. Then, it is put into the refrigerator freezer (about −18 °C) for one night. Later on, the steel plate is removed from the refrigerator and quickly placed on the cement concrete pad. The side of steel plate with asphalt faces down and a steel plate pad is set up. The distance between the iron platform and the iron plate plane is 500 mm. Immediately, a 500 ± 1 g iron ball free falls from the edge of platform. The placement is in the center of opposite side of steel plate. The impact of iron ball on the asphalt and gravel is observed.

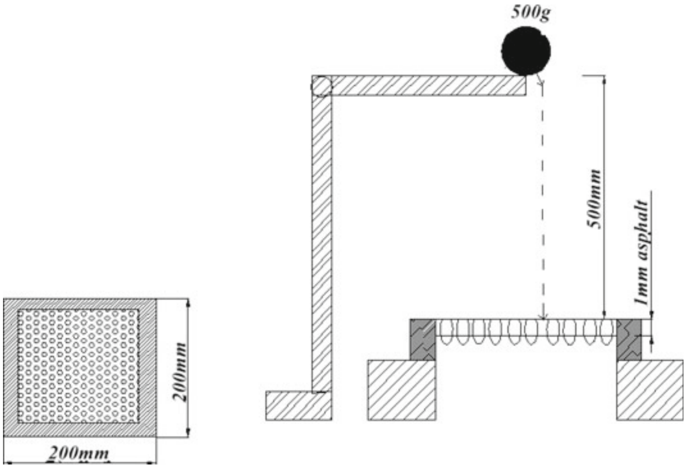

Fig. 4.5 Plate impact test of asphalt and stone at low temperature. Reprinted from Ref. [5], copyright 2003, China Communications Press

Aging Test of Modified Asphalt

Thin Film Oven Test (TFOT) is often used for aging test of pavement asphalt. However, this method is not suitable for modified asphalt because the asphalt is in a quiescent state in the TFOT test. The modified asphalt is often segregated, affecting the aging process of asphalt. So Rotating Thin Film Oven Test (RTFOT) is used, as shown in Fig. 4.6.

Adhesive Test of Asphalt and Stone

In order to improve the adhesion of asphalt with acidic stones such as granite and sandstone, the anti-stripping agent is often mixed with it. In the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering* (JTJ052-2000), according to the asphalt film heating test, the asphalt mixture with anti-stripping agent is heated and aged when the adhesion test of asphalt and aggregate is carried out. Then, the boiling method or immersion method is used to test the adhesion of asphalt and aggregate. It is also stipulated that it is necessary to carry out short-term and long-term agings of the asphalt mixture with anti-stripping agent in accordance with the specified accelerated aging test method in the immersion Marshall test and the freeze–thaw splitting test of asphalt mixture.

Short-term aging refers to the aging of asphalt mixture in the mixing and paving process of construction. Long-term aging refers to the aging process of compact mixture in its service life. In order to compare the aging asphalt mixture with the untreated asphalt mixture, the comparative test of physical and mechanical performances is, respectively, carried out to evaluate the antiaging performance of asphalt mixture.

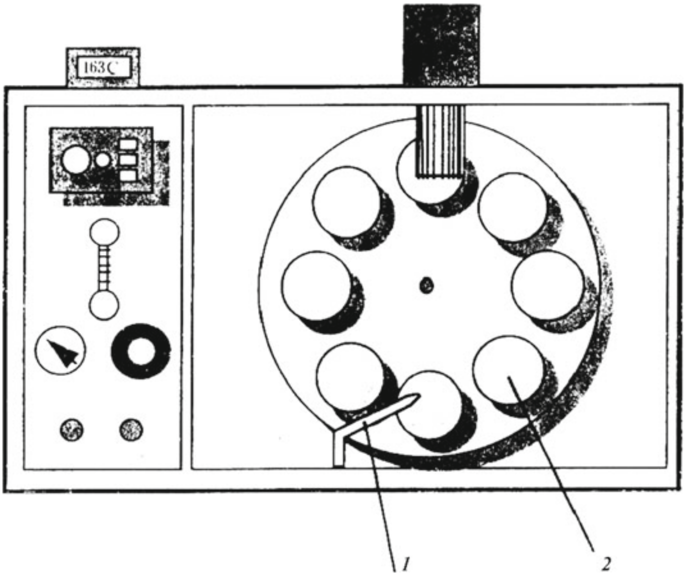

Fig. 4.6 Schematic diagram of rotating thin film oven test. 1, spraying into hot air; 2, rotating bottle. Reprinted from Ref. [5], copyright 2003, China Communications Press

Test procedures formulated by SHRP on the short-term and long-term agings of asphalt mixture are as follows:

Short-Term Aging

According to the requirements of mix proportion, the mixture is mixed and evenly spread in the enamel plate. The thickness of uncompacted layer is about 21 kg/m^2. The mixture is put into the 135 ± 1 °C oven for 240 ± 5 min. The mixture is mixed with a shovel in the specimen dish every 1 h. After 4 h, the mixture is removed from the box for the test.

Long-Term Aging

The short-term aging of mixed asphalt mixture or specimen at the construction site is carried out by the above method. According to the required size and molding method, the specimen is prepared and put into the 60 ± 3 °C incubator for cooling. It is generally cooled for 2 h. Then, the ends of specimen are loaded and flattened at the speed of 72 ± 0.05 kN/min. When its ends are flat or its load is up to 56 kN, the specimen is unloaded at the same speed. It is then placed for 16 ± 1 h and demolded at room temperature. It is placed on a specimen rack and sent to 85 ± 3 °C oven later. It is heated for 120 ± 0.5 h at constant temperature. It must not be touched and moved before cooled. It is cooled to room temperature and removed after not less than 16 h for testing.

4.1.3 Production Process of Modified Asphalt

In general, the production process of modified asphalt can be divided into premixed method and direct input method. One is direct input method such as direct addition of SBR latex, fiber, and ground rubber powder (dry). The other is premixed method.

4.1.3.1 Direct Input Method

Direct input method is that the modifier is directly poured into the mixing pot and mixed with asphalt mixture and mineral aggregate to make the modified asphalt mixture. SBR-polymer-modified asphalt is often made by this method. The intermediate mortar of manufacturing synthetic rubber is concentrated into a high-concentrated latex and transported to the construction site. A pump is used to extract latex which then can be sprayed into the mixing pot through the nozzle.

Simple equipment and low construction cost are required for direct input method. The key technology is the measurement. The latex is easy to block the pipe.

4.1.3.2 Matrix Method

The high-dose polymer-modified asphalt matrix is prepared and then mixed with base asphalt. The specimen is then diluted into the required modified asphalt. It is also known as the secondary blending method.

The advantage of matrix method is that the modifier is evenly dispersed in the asphalt. The disadvantage is that the recovery cost of solvent for the manufacture of matrix is very high, which makes the modified asphalt expensive. In addition, the matrix is not easy to be broken and the engineering application is difficult.

4.1.3.3 Mechanical Mixing Method

The modified asphalt is obtained by mechanically mixing polymer modifier and base asphalt. The mechanical mixing method is suitable for polymers, which is well compatible with matrix asphalt, such as EVA. It requires only a simple agitator. The production depends only on the capacity of agitator. It is suitable for small-scale engineering. It can also be used with a small asphalt mixture agitator.

4.1.3.4 Colloid Mill and High-Speed Shear Method

The modifier is crushed by the grinding of colloid mill or shear force of high-speed shear equipment to make it fully disperse into the matrix asphalt so that the good quality modified asphalt is obtained.

4.1.3.5 Production of Rubber Powder Modified Asphalt

The rubber powder is made of waste tires. The asphalt is mixed with waste rubber powder for the construction of road pavement. The production of waste rubber powder modified asphalt is divided into wet and dry methods.

Wet Method

The waste rubber powder is mixed with 160–180 °C hot asphalt for 2 h to make modified asphalt suspension liquid known as asphalt rubber. It is then added to the mixture. The method is simple. The key technology is to control the fineness of rubber powder. It is easier for finer particles to be mixed evenly and not segregate or precipitate. The rubber-powder-modified asphalt made by wet method is commonly used as filler, sealant, or hot mix asphalt mixture.

Dry Method

The waste rubber powder is directly sprayed into the mixing pot and mixed with modified asphalt mixture. Dry method is only used for hot mix asphalt mixture.

4.2 Material Requirements for SMA

4.2.1 Basic Concept and Formation Mechanism of SMA

4.2.1.1 Basic Concept of SMA

Stone Mastic Asphalt (SMA) is a kind of asphalt mixture with dose skeleton structure which is composed of coarse aggregate, mineral powder, asphalt, and intermediate size particles [4, 6].

SMA is hot mixed and paved. It consists of a large proportion of coarse aggregate which forms a solid skeleton structure, and rich asphalt mastic which fills skeleton for stability. The structure is shown in Fig. 4.7.

4.2.1.2 Composition and Characteristics of SMA

In accordance with the proportion and arrangement of different components, the domestic asphalt mixture can be divided into two categories.

Ordinary Dense-graded Asphalt Mixture

The dense-graded asphalt mixture is based on the principle of continuous gradation which is composed by the index of Fuller equation curve. It is expressed as follows:

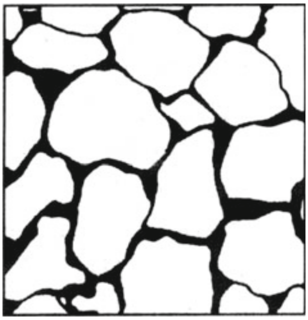

Fig. 4.7 SMA structure. Reprinted from Ref. [4], copyright 1998, China Communications Press

$$p_i = 100\left(\frac{d_i}{D}\right)^{0.45} \tag{4.2}$$

where

p_i the passing percentage of a mesh of total mineral aggregate (%);
d_i the mesh size (mm);
D the maximum particle size (mm).

The dose-graded asphalt concrete in China's current *Technical Specification for Construction of Highway Asphalt Pavements* (JTJ 032-94) is basically in line with this rule. It is suspended dense structure. In theory, the gap of coarse aggregate is filled with a smaller aggregate till the smallest slag. In fact, in order to fill the gap of upper aggregate, much smaller aggregate has squeezed the gap. The finally formed coarse aggregate has less contact and almost suspends in the asphalt mortar mixture. The mixture has a certain gap. The air void (VV) and the void in mineral aggregate (VMA) are the most important volume indices. The structure of suspended dense asphalt mixture is derived from the wedging of coarse aggregate (internal friction) and the adhesion of asphalt mineral binder.

Interlocked Asphalt Mixture

According to the interlocked action of aggregates, China's previous commonly used interlocked asphalt mixture includes penetrating stone asphalt for surface treatment and stone asphalt mixture. This mixture is actually a skeleton gap structure whose principle is only the intercalation between aggregates. The cohesive force only keeps aggregate stable. So the stone asphalt is called asphalt treated and generally used as base.

SMA

SMA is a new asphalt mixture, which is composed of mastic asphalt and stone with dose skeleton structure. It is close to China's stone asphalt mixture with a rich asphalt mastic.

The composition of SMA has the following characteristics [5, 7]:

- SMA is a discontinuous graded asphalt mixture. Such as SMA-16, coarse aggregate particles (>4.75 mm) are as high as 70–80% (30% passing rate). Half of the particles are more than 9.5 mm. The amount of mineral filler is up to 8–13%. The passing rate of 0.075 mm mesh is generally up to 10%. Dust–binder/filler-to-asphalt ratio is much more than the usual limit value of 1.2. Thus, a discontinuous gradation is formed. The fine aggregate is rarely used.
- In order to add much asphalt, the amount of mineral filler increases on the one hand, and the fiber is used as a stabilizer on the other hand, which collectively refers to lignin fiber. The lignin fiber occupies 0.3% of asphalt mixture. The mineral fiber can also be used about 0.4% of asphalt mixture.
- The amount of asphalt binder is 1% more than that of the ordinary mixture. The high adhesion is required for asphalt binder. Small penetration, high softening point, and good temperature stability are required for the asphalt. Using modified asphalt to improve the high- and low-temperature deformation performances and adhesions with mineral aggregate.
- The mix proportion of SMA cannot completely rely on the Marshall mix proportion design method. It is mainly determined by the volume index. Marshall specimen is formed by compacting double face for 50 times. The target porosity is 2–4%. The stability and flow value are not the main indicators. The amount of asphalt can also be determined by referring to high-temperature leakage test. The rutting test is an important means of design.
- Material requirements of SMA: coarse aggregate must be particularly hard with rough surface and less needle-like particles in order to facilitate the intercalation. For fine aggregate, the natural sand is not generally used but hard artificial sand is used. Mineral powder must be ground limestone powder. It had better not use recycled dust.
- Compared SMA with ordinary asphalt concrete in the construction, the mixing time should be properly extended and the construction temperature should be increased.

Characteristics of SMA can be summarized as more coarse aggregate, more mineral filler, more asphalt binder, and less fine aggregate. The fiber-reinforced agent is mixed with it. With high material requirements, the performance of application increases comprehensively.

4.2.2 Material Requirements for SMA

The excellent anti-rutting performance of SMA mainly results from the aggregate itself that has a high degree of internal friction. So, the fine and coarse aggregates are highly required [8].

4.2.2.1 Quality Technical Requirements for Coarse Aggregate

The coarse aggregate is the main material of SMA skeleton, which is required to be tough with hard surface, abrasion resistance, and good intercalation capacity. Its shape is close to a cube. SMA has a high-quality requirement for crushed coarse aggregate with 100% crushing rate. Stone must be tough and angular with high quality and its elongated and flat particles must be strictly limited.

High-quality stone with angular edges is required for coarse aggregate. So the hammer crusher should be used in the crushing operation of SMA coarse aggregate instead of the jaw crusher. In addition, SMA in the majority of cases is used as a wear layer material so the coarse aggregate is required with excellent wear resistance and polishing resistance.

When the coarse aggregate is selected, acid rocks such as granite, quartzite, and sandstone often have good quality but they have poor adhesion to asphalt. Therefore, acid stone is not choose as coarse aggregate. When the acidic stone is used as coarse aggregate, however, the adhesion of asphalt and stone, and the water stability of asphalt mixture do not meet the requirements. Modified asphalt should be used or appropriate amount of lime or cement is mixed. When the anti-stripping agent is used, it must be confirmed that the anti-stripping agent has a long-term water resistance. When the polymer-modified asphalt is used, the water stability of mixture must be qualified or other measures will be taken.

According to *Technology Guide for Construction of Highway Pavement Using Stone Matrix Asphalt* (*SMA Technology Guide*), technical requirements for coarse aggregate of SMA surface layer are shown in Table 4.2.

4.2.2.2 Quality Technical Requirements for Fine Aggregate

Fine aggregate in SMA generally refers to the aggregate below 2.36 mm. Its proportion in SMA is often not more than 10%. Although its proportion is not large, it has a great influence on the overall performance of SMA. In particular, the roughness of fine aggregate has a large effect on the high-temperature rutting resistance of SMA. At the same time, the lack of fine aggregate can also greatly affect volume parameters of mixture and make the air void and VMA of compacting mixture increase, resulting in weakened road impermeability.

China's *SMA Technology Guide* provides that fine material should be used, such as sand that is made by a special fine material crusher (sand-making machine). When the ordinary stone is used, it is appropriate to use limestone chips with a good adhesion to asphalt which do not contain soil and debris. When it is mixed with natural sand, the amount of natural sand should not exceed the amount of sand or stone chips. The particles whose size is less than 0.075 mm in natural sand are not more than 5%. When sand is used as a fine aggregate, the roughness index must be determined to indicate the angular and surface texture of sand. The quality of fine aggregate should conform to the technical requirements of Table 4.3.

Table 4.2 Technical requirements for the quality of coarse aggregate used for surface course of SMA

Indices		Units	Technical requirements	Test methods
Stone crushing value		%	≤25	T0316
Los Angeles abrasion loss		%	≤28	T0317
Visual density		t/m^3	≥2.60	T0304
Water absorption rate		%	≤2.0	T0304
Adhesion with asphalt		Grade	≥4	T0616
Firmness		%	≤12	T0314
Flaky particles content		%	≤15	T0312
Water washing method <0.075 mm particles content		%	≤1	T0310
Soft rock content		%	≤1	T0320
Stone polished value		BPN	≥42	T0321
Particles from different amount of broken layer	Particles from a broken layer	%	100	T0327
	Particles from two or more broken layers		90	

Table 4.3 Technical requirements for the quality of fine aggregate used for surface course of SMA

Indices	Units	Technical requirements	Test methods
Visual density	t/m^3	≥2.50	T0329
Firmness	%	≤12	T0340
Sand equivalent	%	55	T0334
Plasticity index	%		T0118 or 0119
Roughness	s	Actual measurement	T0345

4.2.2.3 Quality Technical Requirements of Fillers

Technical Requirements of Fillers

As the mineral filler asphalt pellets can play a role of dispersion with the help of fiber, the amount of SMA filler is far more than ordinary asphalt mixture. In China's *SMA Technology Guide*, the quality technical requirements for fillers are as follows:

The mineral filler ground by alkaline rocks such as limestone is used for filler. It must be dry and free from the powder silo. Its quality should meet the technical requirements of Table 4.4. In order to improve the adhesion of asphalt binder and

Table 4.4 Technical requirements for the quality of filler used for surface course of SMA

Indices		Units	Technical requirements	Test methods
Visual density		t/m^3	$\geq$2.50	T0352
Water absorption rate		%	$\leq$1	Oven drying method
Size of particle	<0.6 mm	%	100	T0351
	<0.15 mm		90–100	
	<0.075 mm		75–100	
Appearance		%	No pellet, no agglomeration	
Hydrophilic coefficient			$\leq$1	T0353
Plasticity index		%	$\leq$4	T10118 or 0119

aggregate, the amount of lime powder and cement should not exceed 2% of the total mass of mineral aggregate. Fly ash should not be used as a filler for SMA.

Regulations of Application of Recycled Dust

When the dust removal device is used for SMA, the amount of reclaimed powder should not be more than 25% of the total mass of mineral powder. The plasticity index of 0.05 mm powder should not exceed four after the recycled powder is used.

4.2.2.4 Quality Technical Requirements for Asphalt Binder

SMA requires an asphalt binder whose viscosity (consistency) is larger than that of ordinary AC. Requirements of China's *SMA Technology Guide* are as follows:

The asphalt binder for SMA must have a high viscosity. A good adhesion to the aggregate ensures adequate high-temperature stability and low-temperature toughness. It is necessary to use modified asphalt for major projects such as highways and heavy traffic road that are particularly hot in summer or particularly cold in winter.

When the modified asphalt binder is not applied, the quality of asphalt must meet the technical requirements for asphalt pavement of heavy traffic road and adopt the asphalt which is 2 or 5 grades harder than local common asphalt.

When the modified asphalt is engaged, the base asphalt for modified asphalt must meet the technical requirements for asphalt pavement of heavy traffic road. The grade of base asphalt should be determined by experiment. It is usually equal to ordinary asphalt grade or a grade with a slightly larger penetration. After asphalt is modified, the penetration grade should be 40–60 in southern and central regions of China, 40–80 in the northern region, and 60–100 in the northeast cold area.

The quality of polymer-modified asphalt for SMA should meet the technical requirements in the *Technical Specification for Construction of Highway Modified Asphalt Pavements* (JTJ 036-2002). In order to improve the anti-rutting capacity of asphalt mixture as the main purpose, it is desirable that the softening point temperature of modified asphalt is higher than the annual maximum temperature of road surface.

Except special circumstances, the reasonable dose of all kinds of modified asphalt modifier should choose from the following range:

As for modified asphalts such as SBS and SBR, according to the interpolation method, the modifier dose should be 3.5–5%. As for modified asphalts such as EVA and PE, the modifier dose should be 4–6%.

4.2.2.5 Fiber Stabilizer

Category and Role of Fiber Stabilizer

The reinforcing fiber for SMA can effectively improve the high-temperature stability of mixture and resist the wear of tire. It can also improve the density of asphalt mixture and effectively prevent the cracking and water seepage. In the absence of fiber, modified asphalt can be used instead but cannot completely replace fiber.

Now, there are more types of fiber used in asphalt mixture, mainly including lignin fiber, mineral fiber, and organic fiber.

Main Role of Fiber Stabilizer

Reinforcing Effect

The fiber is mixed in the SMA. It exists in the mixture as a three-dimensional dispersed phase as if the peasant builds a mud house, and straws are added to the plaster. Like geogrid and geotextile, reinforced materials can also play a reinforcing role.

Dispersion Effect

If there is no fiber, plenty of asphalt powder is likely to become a micelle. It cannot be evenly dispersed in the aggregate. When it is paved on the road, "oil spots" will exist. The fiber can make micelles appropriately disperse.

Absorption Effect

The fiber stabilizer is added to SMA to fully adsorb asphalt in both surface and internal. Therefore, the amount of asphalt increases and its oil film thickens so as to improve the durability of mixture.

Stable Effect

The fiber makes the asphalt film in a relatively stable state. Especially, in the summer, when the asphalt is heated to expand, the fiber inside the gap will also become a buffer room so that the asphalt cannot become free and leak. It is also good for high-temperature stability.

Adhesive effect to improve the adhesion force

The fiber can increase the adhesion of asphalt and mineral aggregate. Through the bonding of oil film, the adhesion force between the aggregates is improved.

Types of Fiber Used in Asphalt Mixture

Methyl Cellulose

Methyl Cellulose (MC) is an organic fiber through the chemical treatment of natural woods. As the treatment temperature is up to 250 °C, it is a chemically very stable material and cannot be corroded by the general solvent, acid, and alkali under normal conditions. Untreated MC is also used as food additives. It is also a weight-loss food. So it is harmless to both the human body and the environment.

At present, German JRS Company is the leading fiber manufacturer in the world whose main production is lignin fiber with 80% market share. Because China has little research on the product quality of lignin fiber, there is no standard of lignin fiber. Therefore, foreign product standards are temporarily adapted. Some companies in China developed loose lignin fiber, such as Baoheng Technology Development Co., Ltd., Highway Bureau, Jilin Province. After the identification, it has been used in some projects in Jilin and Shandong Provinces, which achieves good results. Other areas have also begun to cooperate with the timber fiber plant for the development of lignin fiber and special equipment used in SMA, such as the development of fiber-added equipment in Hebei Province in China.

Mineral Fiber

In mineral fibers, asbestos fiber is the earliest used one. Compared with other fibers, the price of asbestos fiber is cheaper. It is easy to moisture and cluster in long stacking. In addition, the asbestos dust is harmful to the human body and the environment. It must be strictly managed. Developed countries have banned the application of asbestos fiber.

Polymer Organic Fibers

In organic chemical fibers, polyester and acrylic fibers are the most commonly used ones. Scientific research and application practice in the highway show that the performance of asphalt mixture has generally improved with these fibers, such as Boni fiber and Dolanit as fiber. The fatigue life is increased by 25–45% and the rut is reduced by 45–53%.

Fibers in the asphalt mixture play the role of stability and reinforcement. The mixture carries about 0.20–0.3% fiber which is 1.50–2.72 kg fiber per ton of mixture. Due to the role of fiber, the asphalt dosage increases by 0.2–0.3%.

Comparison of Various Fibers

The performance of lignin, mineral, and polymer fibers is compared from the following aspects:

The first one is oil absorption performance. The oil absorption performance of lignin fiber is better than that of mineral and polymer fibers. It is related to the prevention of free asphalt leakage. The surface of lignin fiber is rough and the surface area is large. The oil absorption performance is good. But the lignin fiber is easy to degrade and absorb moisture. In addition, it is difficult to produce asphalt mixture in the future. Therefore, the application of lignin fiber also caused some doubts.

As for price, the price of lignin fiber is more expensive than that of mineral fiber but the relative density of mineral fiber is larger so more mineral fiber is consumed. Polymeric fiber is the most expensive one but the density is small. The number of polymeric fiber unit mass is largest and its consumption is smallest. Generally, the amount of lignin fiber is 0.3% of asphalt mixture. The mineral fiber occupies 0.4% and polymer fiber occupies 0.20–0.3%. The specific amount is determined by the test.

As for the construction, the fiber is mainly evenly dispersed into the asphalt mixture to play its role. For example, there are granular and loose lignin fibers. The shortcomings of loose fiber in the transport process are easy to agglomerate and absorb moisture. If you do not pay attention to them, the application of loose fiber is a problem. Granular fibers can solve the shortcomings of loose fibers but the particles are difficult to disperse in the short mixing process. But, if there is a dedicated equipment to add loose fiber, loose fiber may be more effective. If there is only artificial way without equipment, the addition of granular fibers will be much more convenient. In short, it is analyzed according to the specific conditions and construction process of engineering construction companies.

In the special heavy traffic and extremely harsh climatic conditions, the performance of ordinary asphalt mixture cannot meet the requirements of pavement. It is necessary to further improve the pavement performance of asphalt mixture. Practice has proved that it is an effective way to use new asphalt composite materials such as modified asphalt and modified asphalt mixture (such as Stone Asphalt Mastic [SMA]).

4.3 Design Process and Construction Control of Mix Proportion of Asphalt Mixture

4.3.1 Design Process of Mix Proportion of Asphalt Mixture

The design of mix proportion of asphalt mixture should follow the three steps in the existing specifications to design proportion of hot mix asphalt mixture. That is, target proportion design, production proportion design, and production proportion

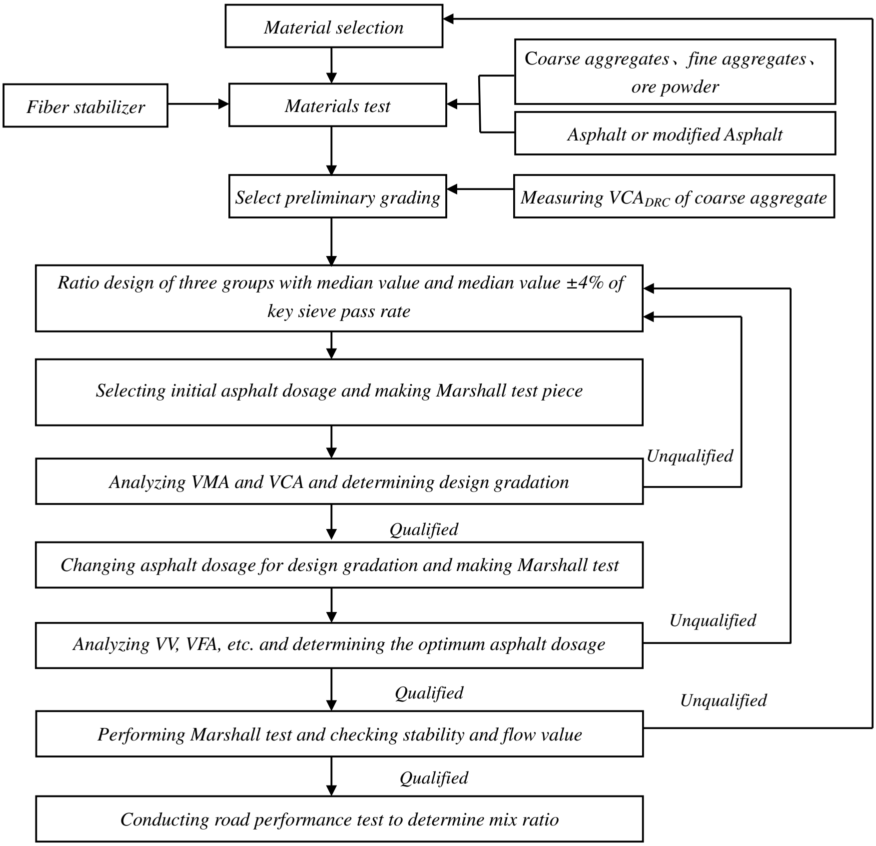

Fig. 4.8 Target mix design flow chart of SMA mixture. Reprinted from Ref. [5], copyright 2015, China Architecture and Building Press

verification. The purpose of proportion design of asphalt mixture is to determine the gradation of aggregate and the optimum asphalt content.

4.3.1.1 Design of Target Proportion Design

The design steps of target: proportion of SMA is shown in the flowchart of Fig. 4.8.

4.3.1.2 Design of Production Mix Proportion and Verification of Production Proportion

The design of production proportion and the verification of trial mix and pavement of SMA are basically the same as those of ordinary hot mix asphalt mixture. They can refer to the common approach. Based on the design results of target proportion, they should be carried out according to *Technical Specification for Construction of Highway Asphalt Pavement*.

The design of production mix proportion should be based on the material gradation of hot aggregate bin after the second screening. The water washing method should also be used to determine the content of fine powder whose size is less than 0.075 mm. The design steps of proportion are the same as the design methods of target proportion. The gradation of mineral aggregate and the amount of asphalt should be similar to the target proportion design to reduce the test workload.

The asphalt–aggregate ratio determined by the design of production mix proportion must be checked by the design of proportion and confirmed by the pavement of test road. It should also be noted that the quantity of the added fiber is checked. Trial mix and pavement must be implemented by the engineering management company, construction company, supervision company, and other relevant parties to determine the standard proportion mix. It must be approved by the supervision engineer. After the approval of standard proportion mix, it should not be arbitrarily changed in the production process. If there is any doubt, it must be approved to adjust the standard proportion mix by the supervision engineer and development organization company (construction unit).

4.3.2 Construction Control of Asphalt Mixture

4.3.2.1 Construction Preparation

Physical and mechanical properties of raw materials are tested. Various types of designs of target mix proportion are completed [9].

The quality detection of material: the detection of material source and material approach. The design of target proportion mix should be completed a month before the start of asphalt pavement.

Materials Field and Preparation

The area of materials field is more than 35 acres. The crushed aggregate is divided into five warehouses. The total storage amount of crushed stone is more than 100,000 t. The tank storage capacity of asphalt is not less than 300 t.

The site is required to be hardened, especially the road transport trucks pass. When transport trucks come into the pavement, tires cannot be stained with soil and other possible pollutions to the road surface or tires should be cleaned up before coming into the project site.

Equipment Debugging

Machinery and test equipments are debugged and calibrated, especially the temperature of mixing equipment, weighing system measurement calibration.

4.3.2.2 Planning and Construction of Mixing Plant

Social road resources are used as far as possible. The main line should avoid driving to prevent the road base from being damaged.

Mixing field must be hardened and planed uniformly. Different materials must be strictly separated for storage, and not mixed. The road of mixing field must be smooth. Before the start, sufficient qualified crushed stone, filler, asphalt, and other materials should be prepared. The material shed of fine aggregate (shed specification: not less than 40 m × 80 m × 7 m) should avoid rain and pollution.

The mixing field should attach great importance to the environment and have adequate power, which is far away from the residential area.

4.3.2.3 Construction Equipment

The intermittent agitator is used. The hourly output is not less than 270 t. It is equivalent to type 4000. The annual construction capacity is about 20–25 km/year.

- There are no less than four hot aggregate warehouses and no more than two mineral fillers;
- The dust collection device has secondary dust removal equipment;
- With the storage capacity of more than 150 t can keep warm;
- The mixing of mixture should be controlled by a computer.

There are three pavers (two pavers are required in the lower pavement. One paver is required in the middle and surface pavement, respectively. The paving width is adjustable from 12 to 16 m). The paver should meet the requirement of controlling the paving thickness and flatness of mixture pavement.

The rollers include vibratory roller: a roller with double cylinder, double drive, and double vibration. It should be 10–13 t (for the lower, middle, and upper layers). The amplitude and frequency are adjustable. There are generally three rollers.

Pneumatic tired roller: 26–30 t. There are not less than three rollers for the middle and lower pressures.

Portable small vibratory roller or ram: one piece for the rolling of corner.

Transport Vehicle

The total capacity is not less than the production of agitator. The load of each car is not less than 15 t. There is warm canvas, quilt, etc., equipped for waterproof and heat insulation.

4.3.2.4 Test Equipment and Detection

A site laboratory should be established. It must meet the requirements of quality inspection station. The quality inspection of a variety of construction materials can be carried out.

The laboratory should be equipped with a variety of equipment standard tests and on-site quality inspection. The professional test staff are not less than four persons. Test equipment is inspected by the measurement department with reliable quality and high precision.

Test items:

(a) asphalt, (b) Marshall test, (c) asphalt mixture extraction test, (d) particle analysis, (e) water content, (f) density test, (g) elongated and flat particle test, (h) crushing value test, (i) rolling test, (j) anti-skidding performance test, (k) roughness detection, (l) measurement, (m) road deformation, (n) temperature measurement, and so on.

4.3.2.5 Mixing and Transporting

Preparation of Asphalt

The heat conducting oil should be used to heat asphalt. The asphalt temperature should be stable: ordinary asphalt heating temperature (155–165 °C) and modified asphalt heating temperature (170–185 °C). The modified asphalt should be used after being stirred.

Aggregate Preparation

- The aggregate is scraped in the direction which is perpendicular to its flow direction to ensure that it is evenly scraped and avoid its segregation.
- The water content should be detected before the start. The feeding rate of cold aggregate is adjusted, according to it, the heating time and temperature are determined.
- When the aggregate gradation changes or new materials are used, the mix proportion should be redesigned.
- Aggregate should be heated to make the asphalt mixture meet the requirement of ex-factory temperature.

Mixing

- The temperature of aggregate, asphalt, ex-factory temperature of mixture, paving, and rolling should meet the requirements.
- Mixing time: aggregate is wrapped by asphalt film. There is no white asphalt crumb. It is black and shiny.
- The mixing homogeneity is checked, such as white, yellow, or dark aggregate.
- There is storage warehouse to ensure continuous construction.
- Mix proportion of asphalt mixture is controlled.
- The oil consumption, the amount of hot aggregate, and the total mass of mixture are printed one by one.

Transport

- The transport capacity per hour must be larger than the production of agitator and adjusted with the shipping distance.
- The truckload of asphalt mixture should be more than 15 t and have tightness, clean and smooth metal floor. The floor should be coated with a thin layer of diesel oil and water (the ratio of diesel oil and water can be 1:3). The mixed solution or watering powder solution (watering powder solution is better) is used to prevent the mixture from sticking to the floor, but the bottom of truck must be cleaned up. Before loading, hydrops in truck floor should be drained up.
- All drivers should be trained. The truck must be strengthened maintenance and avoid the breakdown in the transport. When the aggregate is installed, the transport truck should move front, and back, then middle in accordance with the order in order to avoid the segregation of mixture. The transport truck should stop at the position of 10–30 cm in front of the paver. It should not knock the paver. In the unloading process, it should be linked and pushed forward by paver to ensure the flatness of paving layer.
- After loading the mixture, the temperature should be timely tested. When the temperature is too high, the burned mixture without viscosity should be abandoned.
- The transport truck in front of paver should wait for unloading. When the pavement begins, more than five transport trucks wait for unloading to ensure continuous paving.
- When the aggregate is transported to the paving site, it should be received by leaflets. The quality of mixing is also checked. The mixture which does not meet the requirement of temperature or is wet with lumps should be abandoned.
- The transport truck should be driven in a solid road to reduce its bumps. Regardless of low- or high-temperature season, it must be covered.

Paving

- Lower layer paving: the base cracks are properly handled. The excess stone, dirt, residue, and pollution on the seal coat must be removed. The serious pollution must be washed or cleaned by air compressor. An iron control pile at the position of 5–10 m on both sides of paver is set, respectively. The ultrahigh section is appropriately encrypted. A unified rope is tensiled according to the thickness of loose layer. One end is fixed and the other end is tensile. The tension is not less than 100 kg.
- When the pavers operate at the same time, the road line of first (front) paver is set as follows: wire rope is used at the edge and aluminum alloy beam is used in the middle. The road line of second (back) paver must be set as follows: wire rope is used at the edge and skid is used in the middle.
- Before the mixture of upper layer is paved, mud and debris of lower layer should be cleaned and washed. The emulsified asphalt tack should be sprinkled 0.5–1 s in advance (sprinkling time should not be too early to lose tenacity!). A small or excess amount is not allowed to ensure that the sticky oil has been demulsified when the mixture is paved.

- When the elevation and smoothness control of lower and middle layers are better, the paving of upper and middle layers does not need to pull the wire to control elevation. The bilateral balance beam and skid can be directly used for automatic control and elevation.
- According to the thickness of uncompacted layer, and longitudinal and horizontal slopes, the initial state of paver is adjusted before the paving. The thickness of uncompacted layer of each paver is determined according to the trial paving.
- The echelon paving is used in lower and middle layers. A paver is used in upper layer. The two pavers had better be the same model. The distance between two pavers is 5–10 m. The paving distance at high temperature can be longer while it should be shorter at low temperature. When the modified asphalt mixture is paved, the distance between two pavers should not be too long about 5 m. Two adjacent pavers should be overlapped about 5–10 cm.
- The paver should be equipped with hopper of sufficient volume to ensure uniform continuous paving. After the unloading of last truck is finished, the next truck can timely provide mixture so as not to stop working for mixture.
- The flat plate or leveling unit can effectively pave the decorative surface with the required flatness and texture without tearing, pushing the mixture, or causing holes.
- The paving speed of mixture should be coordinated with the feeding speed of agitator to maintain uniform uninterrupted paving without halfway downtime.
- The paver is equipped with a flat automatic control device and a sensor on one side or both sides. Through the outside referent line, the horizontal slope and the longitudinal slope of flat plate are detected. The signal can be automatically given out to operate the flat plate. The paver can lay out the ideal longitudinal slope. The horizontal slope controller should allow the flat plate to maintain an ideal slope with an accuracy of $\pm 0.1\%$.
- Each paver should be equipped with two automatic leveling devices (contact balance beams) whose length is larger than 16 m or noncontact balancing units. They are firmly set on both sides of paver and combined with automatic control sensor of flat plate to control the paving thickness and flatness of mixture.
- In irregular areas and secondary areas, when the automatic control system cannot work properly, the manual control is allowed to use.
- The contact surfaces on the road edge, side ditch, water well, and other structures should be evenly coated with a thin layer of asphalt and then pave the asphalt mixture on these contact surfaces.
- The paving temperature of asphalt mixture should meet the requirements of specifications and reasonably select according to asphalt grade, viscosity, temperature, and thickness of paving layer. When the air temperature is below 5 °C, AC-25C asphalt mixture cannot be paved. When the air temperature is below 10 °C, the modified asphalt mixture such as AC-20C and SMA13 cannot be paved.

- The thickness of paving layer and horizontal slope should be tracked and checked in the paving process. If anything does not meet the requirements, it should be adjusted according to the paving situation in time.
- The longitudinal joint between the middle and lower layers should be staggered about 15 cm.
- During the paving process, the feeding port of hopper should be fully opened. The spiral feeder of paver should not stop working. The speed should not be too slow and the height of mixture is 1/2–2/3 of the height of spiral feeder to ensure that the segregation does not occur on the full width end of paver. According to the required thickness of hot plate, it cannot be randomly adjusted when fixed.

Rolling

- It meets the requirements of compactness and flatness. The flatness index cannot be too high and the compactness must meet requirements. The rolling thickness is generally not larger than 10 cm each layer. As for flexible base, it can enlarge to 12 cm but a special rolling process and methods must be used.
- The reasonable combination of rollers and rolling steps should be chosen in order to achieve the best rolling effect. The combination of drum static roller and tire roller or vibratory roller should be determined by the test.

Initial Rolling

- It should be carried out at high temperature after the mixture is paved without moving and cracking. The rolling temperature must meet the requirements.
- The roller should compact from the outside to the center and overlap 1/3–1/2 width of adjacent wheels. Finally, the central part is compacted and the full progress is completed for one time.
- The light drum roller should be used or the vibratory roller closes the vibrating device and compacts for 1–2 times. The line pressure should not be less than 350 N/cm. After the initial rolling, the flatness and road arch are checked. If necessary, it must be properly trimmed.
- The driving wheel should face the paver when compacting. Compacting lines and directions should not abruptly change to cause the mixture to move. The roller must start and stop slowly.

Re-rolling

- For the lower and middle layers, the re-rolling should combine vibration roller with heavy tire roller. Rolling times should be determined by the trial rolling to achieve the required compactness and porosity without obvious track.
- When tire roller is used, the total quality should not be less than 25 t. The tire inflation pressure is not less than 0.5 MPa and the adjacent rolling belt should overlap 1/3–1/2 width of wheel.
- When three-wheel drum roller is used, the total quality should not be less than 12 t. The adjacent rolling belt should overlap 1/2 width of back wheel.

- When vibratory roller is used, the vibration frequency should be 35–50 Hz and the amplitude should be 0.3–0.8 mm. According to the type of mixture, temperature, and layer thickness, thick layer should select larger frequency and amplitude. The overlapping width of adjacent rolling belt is 10–20 cm. When vibration roller reverses, it should stop vibrating and start to vibrate in the other moving direction to avoid forming a hump for mixture.

Final Rolling

In order to eliminate the track and improve the flatness, the double-wheel drum roller or vibratory roller can be used in the final rolling, which closes its vibration for over 2 times.

Precautions

- The length of rolling section of roller is balanced with the paving speed and remains generally stable.

When it is high temperature and small wind, the rolling section is slightly longer. When it is low temperature and heavy wind, the rolling section is short. When there is pavement construction of modified asphalt mixture in low-temperature season, the roller must follow the paver and compact. When the temperature is too low, it must not pave.

- When the wheel of steel drum roller is stuck, it can be sprinkled with a small amount of water or washing powder water. The diesel oil is strictly prohibited. Tire roller can be sprinkled with a small amount of vegetable oil. The diesel oil or waste oil is strictly prohibited.
- The roller should not turn around or park for waiting on the unformed pavement. The vibratory roller should be turned off when running on a formed pavement.
- The vibration plate should be used in the bridge, retaining wall, corners, widening part, and other local areas which roller cannot compact completely. The artificial rammer and other additional rolling are also applied on the edge of rain wells and a variety of inspection wells.
- No mechanical equipment or vehicle can park on the asphalt pavement which has not yet cooled. Minerals, oil, and other debris cannot sprinkle there.
- The early construction cracks should be observed at any time on the pavement. The rolling way should be timely adjusted when cracks exist due to overload or moving.

Joint Processing of Asphalt Mixture

- The construction joint and structures joint of both ends must be carefully operated to ensure compactness and smoothness. No obvious joint segregation is produced. Longitudinal joint on upper and lower layers should be staggered for 150 mm (hot joint) or 300–400 mm (cold joint) above. Adjacent horizontal joint of two pieces, and upper and lower layers should be dislocated for 1 m or more. 3 m ruler is used to inspect joint construction to ensure that smoothness meets the requirements.

- Longitudinal construction joint should meet the following requirements:

When echelon operation is used for the longitudinal joint in paving, hot joint should be used. In the construction, there is 10–20 cm width left in the paving part not to\temporarily compact. The elevation datum as the post-paving part is then compacted through cross-stitch to eliminate the stitch.

The longitudinal construction joint on the surface should be straight and stay in the line position of lane area. If possible, the longitudinal construction joint on the lower layer should also be straight and stay in the line position of lane area. Two adjacent layers should stagger a lane. When the longitudinal construction joint is not in the line position of lane area, it should not be carried out at the trails of main lane. The longitudinal joint of upper and lower adjacent layers should stagger at least 30 cm away.

When the half-width construction produces longitudinal cold joint due to special reasons, it should be cut flatly by baffle or cutter. Before the mixture is not completely cooled, the rough selvedge at the edge is cropped. It is not advisable to use a cutting machine for longitudinal kerf after the pavement is cooled. A small amount of asphalt should be coated when the other half is added to overlap on the layer for 50–100 mm. When the mixture is eradicated on the former half, it is compacted from the edge to the center with 100–150 mm left. It is then compacted completely by crossing the joint. The new pavement about 150 mm on the already compacted road can be also compacted by walking and then new pavement is compacted completely.

- Horizontal construction joints are mainly working joints.
- Horizontal construction joints of two adjacent pieces, and upper and lower layers should be dislocated over 1 m. A vertical flat joint should be used in the upper layer and a flat joint should be used in the horizontal joint on the middle layer.
- The flat joint should be tightly bonded, fully compacted, and connected smoothly. The following ways can be applied:

At the end of construction, the paver lifts the screed slightly about 1 m away from the end and leaves. The end mixture is shoveled flatly and then compacted. Then, 3 m ruler is used to check the flatness. When it is not yet cold, any part of end layer whose thickness is not enough and then vertically eradicated so that the next construction is connected at right angle.

When joints are paved, some hot mixture can be paved in the rolling part to preheat and soften so that the bonding of old and new mixtures can be strengthened. But, the preheating mixture should be removed before the rolling starts.

Before the mixture continues to pave from the joints, 3 m ruler is applied to check the flatness of end. When the flatness does not meet the requirements, the pavement should be cleared. The reserved height should be adjusted in paving. After the joints construction, 3 m ruler is then used to check the flatness. If anything does not meet the requirements, it should be immediately treated before the mixture has not yet been cooled.

- Two or three steel drum rollers for horizontal rolling should be first used in the horizontal joint. The outside of rolling belt should be placed with a sole timber for the roller. The roller is on the compacted mixture layer in rolling and stretches into new layer for 15 cm. Every time, the roller moves to the new paving mixture for 15–20 cm. When it moves to the new layer completely, the longitudinal rolling is then carried out. When the adjacent paving layer has been formed with longitudinal joint, the steel drum roller can be first used to compact the longitudinal joint with rolling width of 15–20 cm. Then, it compacts along the horizontal joint, and finally along the normal longitudinal joint.
- The lap length of oblique joint is related to layer thickness. It should be 400–800 mm. A small amount of asphalt should be sprinkled in the lap joint. The coarse aggregate particles of mixture should be removed and replaced by the fine material. The lap is flatly jointed and fully compacted. The steps of stepped joints are milled and sprinkled with asphalt. The lap length should not be less than 3 m.

Exercises

1. Briefly describe the differences of road performance between SBS-modified asphalt and the original asphalt.
2. What are China's evaluation methods of characteristics of modified asphalt?
3. Briefly describe the composition characteristics of SMA.
4. Briefly describe the main role of adding fiber stabilizer into asphalt mixture.
5. Briefly describe the construction and processing characteristics of SMA.
6. Briefly describe preparation work of SMA pavement construction.
7. The asphalt–aggregate ratio of asphalt mixture is 5%. Calculate the asphalt content.

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Chapter 5
Polymer Matrix Composites

5.1 Polymer Matrix Materials

5.1.1 Introduction of Polymer

The polymer is a substance formed by the constituent units repeatedly connected with each other, including plastics, rubbers, fibers, and coatings or adhesives. It is also called high molecular compound or high polymer, which refers to the composition of many macromolecules (the molecular weight is up to 10^4–10^6). In general, the molecular weight of low molecular compounds is less than 500. The molecular weight of polymer is always above 1000. But there is no strict boundary between them [1, 2].

5.1.1.1 Basic Concept of Polymer

Monomer

A low molecular weight compound that can form a polymer.

Such as polyethylene $[CH_2 - CH_2]_n$, where $CH_2 = CH_2$ is an ethylene monomer.

Chain

The smallest repeating structural unit that forms the polymer.

Such as $–CH_2–CH_2–$.

Degree of Polymerization

The number of chains contained in the polymer (n).

It reflects the length of molecular chain and molecular weight of macromolecules. $M = m \cdot n$ (the molecular weight of polymer). m is the molecular weight of chains.

J. Yao et al., *Highway Engineering Composite Material and Its Application*,
https://doi.org/10.1007/978-981-13-6068-8_5

Table 5.1 Molecular weight, melting point, and state relationship of polyethylene

Polymerization (n)	Molecular weight (M)	Melting point (°C)	States at normal temperature
1	30	−183	Gas
3	86	−94	Liquid
10	282	38	Waxy
60	1682	104	Waxy solid
100	2802	106	Brittle solid
1000	28,002	110	Hard solid

Polydispersity

The polymer consists of a large number of molecular chains. The number of chains of each molecule is different. And, the length is not the same and the molecular weight is not equal. The phenomenon that the molecular weight of each molecule in the polymer is not equal is called the polydispersity of molecular weight. The polydispersity of polymer determines its large dispersion of physical–mechanical properties. The molecular weight and properties of polyethylene are shown in Table 5.1.

Average Molecular Weight

Due to the polydispersity, the molecular weight of polymer is expressed by the average molecular weight. Generally, it means the mass average molecular weight obtained from the statistical average mass of macromolecules.

$$\overline{M}_W = \sum W_p M_p = \frac{\sum n_p M_p^2}{n_p M_p} \text{ (composite mechanics theory)}$$

where

W_p the mass rate of molecule with the molecular weight of M_P;
n_p the molecular number with the molecular weight of M_P;
M_p the molecular weight of macromolecules with the polymerization of P.

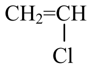
5.1.1.2 Nomenclature and Classification of Polymer

(a) Nomenclature of Polymer

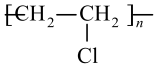
Customary Nomenclature

Add “poly” in the front of monomer name.

Such as $CH_2 = CH_2$ (monomer ethylene) $[CH_2 - CH_2]_n$ polyethylene.



$\mathrm{CH_2{=}\underset{Cl}{\underset{|}{CH}}}$ (vinyl chloride)



$\mathrm{\left[CH_2-\underset{Cl}{\underset{|}{CH_2}}\right]_n}$ (polyvinyl chloride)

Some polycondensates are named by attaching "resin" to the back of name of raw materials:

For example, the product obtained from the polycondensation of phenol and formaldehyde is called phenolic resin.

Commercial Nomenclature

For example, polyethyl lactam is called nylon 6 and polychloroprene is chloroprene rubber.

Systematic Nomenclature (Rarely Used)

Nomenclature International Council of Chemical Association: the repeating structural units of polymer are named in accordance with the organic compound systematic nomenclature and then "poly" is added in front of basic name.

English abbreviation: such as Polyethylene (PE), Polypropylene (PP), Chloroprene Rubber (CR), Styrene–Butadiene Rubber (SBR), and Styrene–Butadiene–Styrene block copolymer (SBS)

According to the performance and application of polymer, it can be divided into three categories:

Plastics—high-polymer material with plasticity. Plasticity is that when the deformation will be produced, the material is affected by external force at a certain temperature, and the shape after deformation will be maintained after the external force is removed. According to the ability of secondary processing, it can be divided into thermoplastic (high-polymer material of linear structure) and thermosetting plastics (high-polymer materials of body structure).

Rubber—high-polymer material with significant elasticity. Under the external force, it can produce large deformation, and after the external force is discharged, it can recover the original shape. According to the production origin, it can be divided into natural rubber and synthetic rubber.

Fiber—linear or filamentous high-polymer material which is flexible, slender, and uniform. According to $l_f/d_f \geq 100$, it is divided into natural fiber and chemical fiber (including artificial fiber and synthetic fiber).

(b) Formation Reaction of Polymer

The reaction that the low molecular weight compound (monomer) is polymerized to form a polymer compound is called polymerization. Common polymerization includes addition polymerization and condensation polymerization.

- Addition polymerization: refers to the reaction that the polymer is produced by polymerizing unsaturated olefin monomer. There is no small molecule produced in the reaction.

- Condensation polymerization: refers to the reaction that the polymer is produced by mixing one or more monomers and a certain low molecule (such as water, chlorine, alcohol, hydrogen chloride, etc.) is precipitated (shrunk).

(c) Polymer Structure and Physical Mechanical State

Types of Polymer Aggregation Structure

Aggregation structure refers to the geometrical arrangement and stacking of macromolecules within the polymer. According to the spatial arrangement of molecules, polymer can be divided into crystal structure and amorphous structure, but usually both crystal and amorphous often coexist.

Mechanical Properties of Linear Amorphous Phase Polymer

The characteristics of molecular motion are mainly determined by the temperature. When the temperature changes, the polymer presents different mechanical states due to the change of mechanical behavior.

According to the different geometric structures, products of condensation polymerization can be divided into:

Linear polycondensation (product has a molecular chain of linearity) and tridimensional polycondensation (molecular chains of product are cross-linked into network or three-dimensionally cross-linked).

Figure 5.1 is deformation–temperature curve that the linear amorphous phase polymer is affected by a constant stress. It is also known as thermodynamic curve.

Figure 5.1 shows that there are the following three physical states at different temperatures:

- Glass state: when the temperature is very low, there are great forces between the molecular chains, so the molecular chain and chain forging cannot move. The solid polymer with amorphous phase is called glass state. When it is glass state, the temperature at which chain forging begins to move is called glass transition temperature (T_g). The temperature that is below it, the polymer cannot be stretched

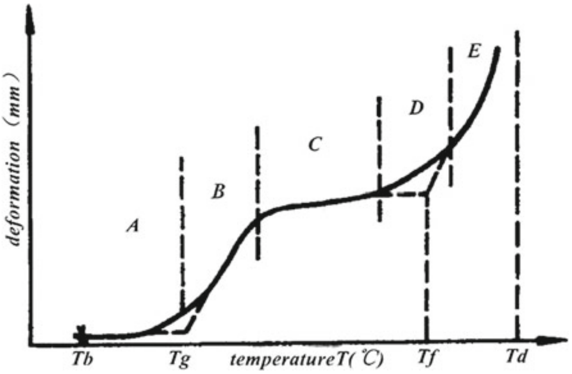


Fig. 5.1 Linear amorphous phase polymer thermodynamic curve+. Reprinted from Ref. [2], copyright 2003, Chemical Industry Press Material Science and Engineering Publishing Center

or bent at a certain temperature which is known as brittle temperature or brittle point (T_b)

- High elastic state when the temperature exceeds glass transition temperature, with the increase of temperature, the chain forging of polymer can be rotated. The polymer becomes soft and has a great flexibility (up to 1000%). The deformation produced by external action can recover to the original state after the load is discharged. This state of polymer is called high elastic state.
- Viscous flow state: when it reaches to flow temperature (T_f), the polymer is extremely viscous liquid. This state is called viscous flow state. At this state, the molecules can slide against each other and molecular chains and chain forging can move. When there is an external force, the deformation is produced by sliding of molecules. When the external force is discharged, the deformation cannot be restored. This deformation is irreversible and so it is called viscous flow deformation.

In conclusion: the polymer in the glass state at room temperature is usually used for plastic or fiber. The temperature of application ranges between brittle temperature (T_b) and glass transition temperature (T_g). It usually refers to heat resistance of plastic, that is, the glass transition temperature.

The polymer in a high elastic state at room temperature is suitable for use as rubber. The temperature of application ranges between glass transition temperature (T_g) and flow temperature (T_f). The minimum temperature of application (T_g) is often known as the cold resistance index, and the maximum temperature of application (T_f) is called heat resistance index of rubber.

In the engineering, viscous flow state is not the applied state of polymer, but the process state. T_f determines the difficulty of forming and processing of polymer. The polymer in the viscous state at room temperature is flow resin. Various products can be made by flow resin through spinning, blow molding, injecting, extruding, etc.

Aging of Polymer

Due to the effect of light, heat, air (oxygen and ozone), etc, there are changes in the structure or composition of polymer, which results in a variety of performance degradation, such as discoloration, hardening, cracking, sticking, softening, deformation, spots, less mechanical strength, and so on. It is called the aging of polymer.

The aging of polymer can be divided into molecular cross-linking and degradation of polymer. Cross-linking refers to the process in which molecules of polymer change from a linear structure to a body structure. When this aging occurs, the polymer loses elasticity, and becomes hard and brittle with cracking. Degradation refers to the fracture of molecular chains of polymer. Its molecular weight decreases but its chemical composition does not change. When the degradation is the main process of aging, the polymer will lose rigidity, and becomes soft and sticky with creep.

According to the difference of aging reasons, the aging of polymer is divided into heat aging and light aging. Light aging refers to the phenomenon that when the polymer is irradiated in the sun (especially ultraviolet), some molecules (or atoms) are activated with high energy to an unstable state and react with other molecules by photosensitive oxidation. It results in the structure and composition change, and the performance deterioration of polymer. Heat aging refers to the phenomenon that when the polymer is acted in the heat, especially exposed to the air at high temperature, the molecular chains of polymer fracture and cross-link due to oxidation, thermal decomposition, and other effects. Its chemical composition and molecular structure change so that its performance changes. As a result, the high-temperature resistance and atmospheric stability of most polymers are poor.

5.1.2 Polymer Matrix

5.1.2.1 Classification

There are a variety of classification methods for polymer matrix used in composites. According to the thermal behavior of resin, it can be divided into thermosetting matrices and thermoplastic matrices. Thermoplastic matrix, such as polypropylene, polyamide, polycarbonate, polyether sulfone, polyether ketone, etc, is a kind of solid polymer with linear chain or branched chains. It is soluble, fusible, and can be reprocessed without any chemical change. According to the different structures of aggregation, this kind of polymer can be divided into amorphous and crystal types. But, the crystallization of crystal polymer is not complete, and the crystallinity is usually in the range of 20–85%. Thermosetting matrix is usually liquid or solid prepolymer with a relatively small molecular weight before being made into a final product, such as epoxy resin, phenolic resin, bicarbonate resin, and unsaturated polyesters. Through chemical reaction such as be heated or cured, thermosetting matrix can form insoluble and non-melting polymers with three-dimensional network. This kind of matrix is usually amorphous.

According to the characteristics and applications of resin, it can be divided into general-purpose resin, heat-resistant resin, weather-resistant resin, flame-retardant resin, etc.

5.1.2.2 Selection of Matrix

The selection of polymer matrix should follow the following principles:

Meet the needs of application of product, such as temperature, strength, stiffness, resistance, corrosion resistance, and so on. The matrix with high tensile modulus, high tensile strength, and high fracture toughness is conducive to improving the mechanical properties of composite materials;

Have good wettability and adhesion to fibers and particles;

Easy to operate, such as a sufficient period of application for glue, a long enough storage period for prepreg, small curing shrinkage, and so on;

Low toxicity and irritation; and

Reasonable price.

5.2 Polymer Concrete

Polymer concrete composites had been called plastic concrete in earlier China. It is a collective name of a kind of concrete prepared by combining cement with organic polymers in different ways.

The earliest polymer concrete was used in 1909. In 1924, Lefebure applied for the first patent. According to the composition materials and forming methods, polymer-modified concrete can be divided into three categories [2]:

- Polymer-Modified Concrete (PMC)

It is made by combining cement materials (cement and polymer) with aggregate. That is, the polymer added to the composition of cement concrete.

- Polymer-Impregnated Concrete (PIC)

The low viscosity monomer, prepolymer, and polymer are impregnated into the pores of hydrated hardened concrete and then the cement concrete and the polymer are integrated as a whole through the polymerization.

- Polymer Concrete (PC)

All cement materials are polymers. The polymer and aggregate are combined into polymer concrete.

5.2.1 Polymer-Modified Cement Concrete (Mortar)

The hydration of cement and the curing of polymer are carried out at the same time. They are filled with each other to form an overall structure.

It is divided into the following categories [2]: polymer latex cement concrete, redispersed polymer powder cement concrete, water-soluble polymer cement concrete, and liquid resin cement concrete.

5.2.1.1 Selection of Raw Material

Polymer

The polymer mixed with cement includes natural and synthetic rubber pulp, thermoplastic and thermosetting resin latex, water-soluble polymer, etc. It can be divided into the following three categories:

- Water-soluble polymer dispersion latex: including rubber latex, resin emulsion, and mixed dispersions.

- Water-soluble polymer: including cellulose derivatives (such as methylcellulose or MC, polyvinyl alcohol or PVA, polyacrylates, etc.), calcium polyacrylate, and furfuryl alcohol. Liquid polymer: including unsaturated polyester and epoxy resin.
- The application of polymer is the same as that of addictive. It is mixed with cement, aggregate, and water. Under normal circumstances, its content is about 5–25% of mass of cement. If no defoamer is added to polymer in the ex-factory goods, an amount of defoamer must be added in the later mixing process.

In order to achieve good results for improving the performance of concrete, it is necessary to use organic polymer materials with good adaptability to cement hydration. Thus, the general requirements for polymers are as follows:

No adverse effect on cement hydration;

Having high stability to the high active ions such as Ca^{2+} and Al^{3+} released during the hydration process of cement;

High mechanical stability. For example, it will not break emulsion in the transport and mixing under the high shear effect;

Good storage stability;

Low air entraining;

Forming a film in the concrete or mortar with a good adhesion to cement hydration products and aggregate (and the minimum film-forming temperature should be low);

Forming a film with excellent water resistance, alkali resistance, and weather resistance, and

No rust on steel.

- The quality requirements are shown in Table 5.2.

Characteristics of common polymer are as follows:

(a) Polyvinyl Acetate (PVAC) is easy to hydrolyze in cement and the strength of specimen is seriously damaged in the case of immersion.
(b) Polyvinylidene Chloride (PVDC) has similar characteristics with PVAC, but the damage is lighter.

Table 5.2 Quality requirements of polymer incorporated in cement

Test types	Test items	Specified values
Dispersion test	Appearance	No coarse particle, foreign body, and concretion
	Total solid content	>35% (the error is within ±1.0)
Polymer cement mortar test	Bending strength (MPa)	>4
	Compressive strength (MPa)	>10
	Bonding strength (MPa)	>1
	Water absorption rate (%)	<15
	Permeable capacity (g)	<30
	Length changing rate (%)	0–0.15

(c) The styrene/butanediol copolymer and the propionic acid ethylene have slow action with alkaline medium slowly. The growth of specimen strength under the condition of immersion is just moderate and does not seem to be affected by immersion.
(d) Acrylic polymer under the condition of immersion can maintain its strength and show the performance of hydrolysis. The polyvinylidene chloride produced by copolymerization also has the same effect.

Main Additives

Stabilizer

In the production of most water-soluble polymer dispersion (latex) resin, the anionic emulsifier is used for the emulsion polymerization. Therefore, when these polymer latexes are mixed with cement, a large number of calcium ions can cause deterioration and breaking of emulsion due to the dissolution of slurry. It results in premature aggregation so that the emulsion cannot be evenly dispersed in the cement. Therefore, the stabilizer must be added to stop the deterioration.

Water Resistance Agent

Some polymers (such as latex resin or its emulsifier and stabilizer) have poor water resistance so that the water resistance agent needs to be added when they are used.

Coagulant

When a large amount of latex resin is mixed, it will delay the condensation of polymer cement concrete. So, the coagulant needs to be added to promote the coagulation of cement.

Defoamer

When the latex is mixed with the cement, many vesicles are usually produced due to the effect of surfactants such as emulsifiers and stabilizers in the emulsion. Therefore, an appropriate amount of defoamer must be added.

5.2.1.2 Modification Mechanism of Polymer

The incorporation of polymer in cement mortar or cement concrete can cause a series of changes in the properties of cement mortar or cement concrete, such as increased flexural strength, reduced compressive strength, reduced elastic modulus, reduced rigidity, increased flexibility, improved deformation ability, improved abrasion resistance, improved bond strength, improved durability, etc. The mechanism of polymer-modified cement mortar and concrete is mainly analyzed from the following aspects:

- Due to the addition of polymer, the structure of cement stone changes, which improves the performance of cement concrete.

- There is a chemical reaction between polymer and cement or products of cement hydration, which improves the performance of cement concrete.
- The incorporation of polymer can have an impact on cement hydration, setting, and hardening process, which changes the performance of cement concrete.
- The incorporation of polymer changes the pore structure of concrete and improves the bonding of cement slurry and aggregate, reducing the microcracks of hardened cement slurry and improving the physical and mechanical properties of cement concrete.
- Due to the incorporation of polymer, it can improve the working performance of cement mortar or cement concrete. The water-reducing effect can reduce the water–cement ratio, which improves the physical and mechanical properties of cement concrete.

Due to different categories and amount of polymers, as well as different research methods, the conclusions about the mechanism of the polymer-modified cement mortar and concrete are different. Actually, there is no unified conclusion at present. Meanwhile, polymers from different categories and of different amount have different modifying effects and mechanisms. But, one or more reasons mentioned above may cause the modification of cement concrete.

With regard to the modification of polymer emulsion to the cement mortar and the concrete, the more consistent is that the improvement is achieved by forming a film with high cohesive force between the cement slurry and the aggregate to clog the pores of mortar. The hydration of cement and the film formation of polymer occur at the same time. The interpenetrating network structure is finally formed by intertwining cement slurry with polymer film each other. Polymers with reactive groups may react chemically with the surface of solid calcium hydroxide or the silicate on the aggregate surface. This chemical reaction is expected to improve the adhesion between the cement-hydrated product and the aggregate, thereby improving the performance of concrete and mortar.

5.2.1.3 Technical Performances of Polymer Cement Concrete

Main Performances of Polymer Cement Concrete

Performances Before Hardening

Good Workability
The water–cement ratio which achieves the specified consistency (slump and flow) can reduce with the increase of polymer–cement ratio, which contributes to the increase of strength, and reduce drying and shrinkage.

Suitable Aerosol
It has good effect on increasing the consistency and improving the frost resistance.

Good Water Retention

Good Performance of Anti-bleeding and Anti-separation

Slow hardening sometimes due to retardation caused by various aiding agents (but it does not affect the application; on contrary, it is even favorable in summer).

Performances After Hardening

Light Apparent Density

The density of polymer is lower than that of cement so the apparent density of polymer concrete is also relatively low (usually 2000–2200 kg/m^3). If the light aggregate is used to prepare concrete, it can reduce the structural cross section and increase the span to meet the requirements of light weight and high strength.

High Mechanical Strength

Compared with the benchmark cement concrete, the various kinds of strength of polymer concrete (including compressive strength, tensile strength, and bending strength, especially the latter two) have been significantly improved, which has a significant effect on lightening the thickness of the road or lessening the size of the bridge structure section.

Strong Adhesion with Aggregate

Because of the strong adhesion of polymer and aggregate, hard stone can be used to make anti-skid layer of concrete pavement to improve the anti-slip and anti-wear of pavement. In addition, it can be also made the anti-slip layer of pavement to prevent the slippery and noise of highway pavement.

Good Durability

Polymer used in the concrete can play a role of water blocking and gap filling, which can improve the water resistance, freezing resistance, and durability of concrete.

Main Factors Affecting the Strength of Concrete

- **Polymer–Cement Ratio**

Different polymer dispersions have different optimum amounts of polymer to achieve the same strength. The most commonly used polymer–cement ratio is in the range of 15–20%.

The compressive strength and the elastic modulus tend to increase with the increase of content of polymer dispersion on a research. But it tends to decrease when the content of polymer dispersion reaches a certain degree. The tensile strength and the bending strength increase with the increase of polymer.

- **Methods of Maintenance**

Methods of maintenance have a great influence on the strength of hardened polymer cement concrete. In general, steam maintenance can get a higher strength. The concrete can get the highest strength with water or moisture maintenance followed by air-drying maintenance. This is because the hydration reaction of cement occurs in the early water conservation and then the polymer film can be formed after becoming dry. Most importantly, different maintenance methods have different maintenance effects on various polymer dispersions. If water maintenance is used, such as Polyvinyl Acetate (PVAC) emulsion with poor water resistance, its strength will be greatly reduced.

- **Factors Affecting Shrinkage Deformation**

The shrinkage deformation of polymer cement concrete is much lower than that of cement concrete (without polymer). This is mainly because the surfactant in polymer dispersion has an effect of reducing water. In order to obtain the consistency, less water should be used.

However, some experimental data showed that sometimes the shrinkage value increased when some polymers were used under some special maintenance conditions.

- **Factors Affecting Creep of Concrete**

The mortar creep coefficient of styrene–butadiene rubber emulsion and polypropylene emulsion is smaller than that of the cement mortar. But when the mortar is mixed with vinyl acetate emulsion and butyl maleate emulsion, its creep coefficient is more than twice that of cement mortar at room temperature. At 50 °C, the creep significantly increases, resulting in damage.

5.2.2 Resin Concrete (Mortar)

Compared with ordinary concrete, resin concrete (mortar) has the following characteristics:

No pore is caused by the residual water after the cement hydration.

No moisture is inside the material and better frost resistance.

No alkaline cement is used so the material has a good acid resistance.

Fast hardening and short construction period.

But it costs and shrinks greatly. As for application, it is mainly used for repairing road and bridge.

5.2.2.1 Selection of Raw Material

Polymer

Polymers commonly used as the cementitious materials in concrete include polymer synthesized from monomers of acrylates, methacrylates, and trimethylolpropane trimethacrylate, as well as epoxy resin, furan resin, unsaturated polyester (UP), vinyl ester resin, etc. The corrosion resistance of furan resin concrete is very good and it is mainly used in strong corrosive environment. The viscosity of monomer of methyl methacrylate is small. The fluidity of fresh concrete prepared with the monomer of methyl methacrylate is very good. At the same time, it can be cured at a very low temperature. But the monomer of methyl methacrylate is volatile and flammable with unpleasant odor, which limits its application. In recent years, the recycled polyester (PET) is used to prepare unsaturated polyester and polymer concrete.

When the monomer or its mixture of these polymers is mixed with liquid polymer and aggregate, initiator and accelerator are usually added for the polymerization of monomer or the cross-linking of resin. The gel time of polymer can be changed by controlling the type and the amount of initiator and accelerator. And, the gel time can be used to control the pot life of freshly mixed PC to ensure that the consolidation is completed within a specified time before stripping.

The viscosity of polymer components can be used to control the coating of the aggregate surface. For high-filled mixture, the resin of low viscosity is more reliable. Sometimes, other properties of uncured polymers are also specified such as density, shelf life, content, flash point, and so on. According to American Concrete Association (ACI), epoxy resin used in polymer concrete for bridge deck, parking lot, and the like should meet the requirements for its performances as shown in Tables 5.3 and 5.4.

Filler and Aggregate

Grinding fine calcium carbonate (except for acid-resistant concrete), silica fume, and fly ash can be used as mash.

Requirements for mash:

Moisture content (<0.5%);

No impurity that adversely affects the polymerization of the resin;

The surface adsorbs resin as little as possible;

A certain degree of fineness for filling and improving the rheological property.

River sand, gravel (broken stone), etc can be used as aggregate. The requirements for aggregate is as follows:

Moisture content: 0.5–1.0%;

Table 5.3 Performance indices of uncured epoxy resin

Performance	Indices	Test methods
Viscosity	200–2000 Mpa s	ASTM D-2393
Pot life	10–60 min	AASHTO T-Z37
Flashing point/ °C	>204	

Table 5.4 Physical indices of cured epoxy resin

Performance	Indices	Test methods
Bonding strength/MPa	>7	ASTM C-882-91
Linear expansion coefficient/k^{-1}	$(5–9) \times 10^{-5}$	ASTM D-696-79
Tensile strength/MPa	>14	ASTM D-638-84
Tensile elongation at break/%	>30	ASTM D-638-84
Elastic modulus/MPa	$(4–8) \times 10^{2}$	ASTM D-638-84

No adverse impurity;
The surface adsorbs resin as little as possible;
Higher strength, and
Stability.

Reinforcing Materials

Reinforcing materials can improve the toughness and bending strength of polymer concrete.

Many types of reinforced materials can be used for PC reinforcement, such as reinforcing bar made from steel or fiberglass reinforcing materials, fabric made from steel, fiberglass and polymer fibers, steel fibers, glass fibers, carbon fibers or polymer fibers, etc. Glass fiber, fiberglass fabric, or fiberglass mat are the most commonly used reinforcing materials because of their relatively good durability, strength and chemical resistance, and low cost. At the same time, glass fiber fabric or fiberglass mat is also easy to lay in the mold and can maintain a certain film thickness.

Additives

PC additives include defoamer, infiltrate, plasticizer, low shrinkage additive, UV stabilizer, flame retardant, coupling agent, etc. The additives should adapt to the polymer used. The polymer concrete with methyl methacrylate as plasticizer usually does not need UV stabilizers because the light resistance of polymethyl methacrylate is very good. Coupling agent, such as silane and titanate can promote chemical bonding between the aggregate and the polymer, which generally makes the strength increase by about 10%. Some studies have shown that the bending strength can increase by 35% and the compressive strength can even increase by 60% when coupling agent is used.

In addition, in order to cure the liquid resin, the hardener (cross-linking agent) and the accelerator are generally added. They are usually mixed with the resin respectively. The hardener cannot be mixed directly with the accelerator to avoid the explosion.

5.2.2.2 Performance of Resin Concrete

Performance of Freshly Mixed Resin Concrete

Compared with the ordinary concrete, the fluidity is reduced and the hardening time is 1–3 h. The bleeding and segregation are reduced, and the curing shrinkage increases.

Performance of Hardened Resin Concrete

Mechanical Properties

Compressive Strength

The compressive strength of PC is 60–180 MPa, which depends on the type of polymer, and the size, type, and grade of aggregate. The commonest compressive strength is 80–100 MPa. The filler has some influence on the compressive strength of the polymer concrete. The 28d compressive strength of the polymer concrete is also greatly improved by using cement and fly ash. Calcium oxide is the most unfavorable filler for the strength of polymer concrete. In conclusion, cement and fly ash are ideal fillers.

Bending Strength

The bending strength of PC is affected by the polymer. In general, highly cross-linked polymers have higher bending strength and elastic modulus, which is more prone to brittle fracture. The bending strength of plain PC is 14–28 MPa or higher. PC made from flexible polymer has better toughness than PC made from rigid polymer. The end-reinforced curved member is brittle and its ultimate bending stress should be determined according to the bending test of formulation.

Elastic Modulus

The deformation of PC depends on the elastic modulus and the maximum elongation of polymer. The maximum elastic modulus of the rigid polymer is up to 35 GPa. PC has very good toughness. The impact strength of the material and the ability of absorbing energy before the fracture (expressed by the area under the stress–strain curve) are related to toughness.

Shear Strength

Most shear damage of the PC structure is the same as that of cement concrete, which is actually diagonal tensile or compressive damage. Because PC is similar to cement concrete, its tensile strength is much smaller than the compressive strength. So, it mainly results in the diagonal tensile damage of the pure shear area. At present, the shear strength of PC is 2–26 MPa, between the tensile strength and the compressive strength.

Chemical and physical properties of polymer concrete

Aging

The aging mechanism of polymer is the cleavage of molecular chain, which is usually a very slow process. The aging of the polymer is strongly influenced by ultraviolet radiation and high temperature. Therefore, when affected by ultraviolet radiation and high temperature, PC should be selected according to its antiaging performance. Because the high filling improves the opacity of PC, the degradation due to UV can be reduced. Therefore, the performance of the polymer itself used as cementing agent may not be a good criterion for UV stability. In the United States, the performance of building curtain wall panels and underground utility components made from PC does not seem to be reduced at all after being used for more than 30 years.

Water Absorption and Impermeability

The water absorption of PC is very small, generally 1% (mass) or less. All the freshly mixed liquid components are polymerized into solid at the time of curing so that no initial pores are produced. Most absorbed moisture is present in discontinuous holes in the surface or near surface, which are generated by sandwiched air when mixed or poured. Some studies have shown that the strength of some polymers is reduced after soaking, probably due to the damaged bonding between the aggregate and the polymer. Polymer itself has poor water resistance, so when it is used in PC, it is easy to reduce the intensity with water. Generally, the strength is slightly reduced. For PC with good curing and few pores, the strength will be reduced after a long time.

The permeability of PC is smaller than that of Portland cement concrete or wood, but larger than that of metal, because PC does not have the internal interconnected pore structure. During casting process, the pores are isolated and discontinuous due to sandwiched air.

Freeze–thaw Resistance

The alternation of freezing and thawing can reduce the performance of non-aerated Portland cement concrete. The impact of freeze–thaw cycle on PC is very small because it has no inside hole structure which can absorb or release water. No loss of quality occurred after 1600 freeze–thaw cycle tests were carried out with PC.

Shrinkage Rate

In PC, the volume shrinkage occurs when the monomer or resin system becomes solid from the liquid and PC is cooled from the exothermic polymerization. The volume shrinkage of PC varies with the type and the amount of monomers or resins. The curing shrinkage rate of epoxy resin is small while the curing shrinkage rate of unsaturated polyester resin is big. In order to reduce the shrinkage of the unsaturated polyester resin, an appropriate amount of the thermoplastic polymer may be added, such as using a polyvinyl chloride powder or adding the polystyrene particles to the styrene monomer to form a shrinkage solution. If the amount of filler appropriately increases or the temperature of the curing process decreases, it cannot only reduce the shrinkage of unsaturated polyester, but also change the monomer used in the synthesis process of unsaturated polyester resin. Chemically compensating this contraction can produce unsaturated polyester with low or zero shrinkage.

Heat Resistance

When the temperature rises and is close to or exceeds Heat Deflection Temperature (HDT) of the resin, the performance of the resin changes drastically. At HDT, the resin begins to soften and deform or flow under a certain load. In the preparation of PC, physical properties of PC should be measured in the expected high temperature and low temperature. The thermal deformability of a particular PC formulation can be predicted by using ASTM D648 for measuring its load deformation temperature. For the structural application, HDT should be specified to be higher than the expected maximum temperature in the structural application environment.

Thermal Expansion Coefficient

The thermal expansion coefficient can vary over a wide range. The thermal expansion coefficient of PC with low polymer content (<10%) is small and is mainly affected by aggregate. With the increase of polymer content, the thermal expansion coefficient gradually approaches the value of polymer. At room temperature, the thermal expansion coefficient of PC can change. For a UP with 9% resin, the measurement of PC showed that the thermal expansion coefficient was about 11×10^{-6} K^{-1} at room temperature and about 15×10^{-6} K^{-1} above room temperature. The thermal expansion coefficient of PC can range from 13×10^{-6} to 126×10^{-6} K^{-1}. The linear expansion coefficient of PC is usually 1.5–2.5 times that of steel or Portland cement concrete. This performance is important for PC structures (such as building exterior panels) that are rigidly connected to other materials.

Chemical Resistance

One of the valuable properties of PC is its chemical resistance. The choice of aggregate and polymer can affect the chemical resistance of PC. Polymers are chemically inactive materials. Most PCs are resistant to alkali, acids, and many other corrosive media such as ammonia, petroleum products, salt, and some solvents, but not resistant to oxidizing acids (such as nitric acid and chromic acid). The oxidizing acid can react with most of polymers, including the phenolic polymer and the polyester-based polymer. In acidic environment, the acid-resistant aggregate should be chosen. Organic solvents can erode most of the commonly used polymers, thereby making it to swell or even damage it.

5.2.3 Polymer-Impregnated Concrete (Mortar)

Polymer-Impregnated Concrete (PIC) is a kind of polymer concrete composite that is generated by the polymerization after the hardened dry concrete which is impregnated in the polymerizable low molecular monomer or prepolymer. The research and development of PIC began in 1965 and was developed by Brookhaven laboratory and National Development Agency of USA. Then, the application research of PIC has raised the world's attention. A large number of research results show that PIC is a kind of organic and inorganic composites with high strength, impermeability, chemical resistance, freeze–thaw resistance, and abrasion resistance.

5.2.3.1 Selection of Raw Materials

In general, liquid materials that can be absorbed by concrete substrates and be polymerized into the solid can be used to impregnate concrete. Commonly used polymer monomers include methyl methacrylate, methyl propylene, styrene, etc. Commonly used prepolymers include unsaturated polyresin and epoxy resin. A monomer, several monomers, or a mixture of monomers and polymers can be used as the impregnation solution. In addition to the monomer, an initiator, a promoter, a cross-linking agent, and a diluent can be also contained in the impregnation solution.

The general requirements for polymer materials are as follows:

Lower viscosity. Polymers can easily penetrate into the substrate. The lower the viscosity is, the easier the infiltration is, and the larger its depth is. In the local impregnation, high viscosity polymer can be chosen.

High boiling point and low vapor pressure to reduce the loss after impregnation and polymerization.

Good adhesion with the substrate to form a whole after polymerization.

Small polymerization shrinkage. The formed polymer should have higher strength, and good water resistance, alkali resistance, aging resistance, and other performance.

The softening temperature of the polymer should exceed the temperature at which the material is used.

5.2.3.2 Preparation Technology of Impregnated Concrete

The preparation technology of impregnated concrete can be divided into three parts: preparation of concrete substrates, impregnation, and polymerization.

Preparation of Concrete Substrates

The impregnated concrete substrates are mainly cement concrete products, including reinforced concrete products. The production process is the same as the general prefabricated components of concrete. The concrete substrate for impregnation should meet the following requirements:

- There is no component which hinders the polymerization of impregnation solution.
- There is a certain basic strength that can withstand the stress in the dry, dipping, and polymerized process. There is no crack and other defects in handling.
- There are appropriate pores that can be filled with impregnation solution. The material structures are as even as possible.
- The size and shape of components adapt to the methods and equipment of impregnation and polymerization. The thickness of substrates is generally not more than 15 cm.

Impregnation

In order to ensure the adhesion of polymer to the concrete, the monomers of polymer are penetrated into the pores in the concrete. The substrate must be thoroughly dried before the impregnation. The main steps in the impregnation process include drying, evacuating, and impregnating.

Drying

Drying method is generally hot air drying. The drying time depends on the drying temperature, the thickness, and shape of components. The moisture content of the concrete is usually not more than 0.5%, and the drying process can be determined by the experiment.

Drying temperature should be controlled between 105–150 °C. When it is over 150 °C, the strength of concrete and impregnated concrete will decrease with the increase of temperature.

Evacuating

The evacuating purpose is to remove the air that prevents the monomer from infiltrating from concrete pores, and to facilitate the impregnation.

Impregnating
According to the purpose of impregnated concrete, it can be divided into two kinds: complete impregnation that concrete section is completely impregnated by the monomer, and partial impregnation that the monomer only penetrates into a certain depth, generally below 10 mm, closing the surface pores of concrete, and improving its durability, impermeability, and corrosion resistance. In addition to the above purposes, complete impregnation can also improve the strength of concrete.

Polymerization
Polymerization is a process of converting the monomer of concrete into the solid polymer. The principle of polymerization varies with the type of impregnation solution. For the monomer system containing double bonds, the polymerization is to initiate the double bond to open and carry out the chain addition reaction. For the impregnation solution, such as epoxy resin whose monomers have no double bonds, polymerization is to initiate the reaction of the resin and the cross-linking agent.

The polymerization can be caused by radiation method, heating method and chemical method. Compared with radiation method and chemical method, heating method needs less investment and can be applied easily and at a fast speed, so it is widely used. Chemical method is more suitable for large-scale processing site because the monomer cannot be reused. In the heating polymerization, the temperature should not be too high because the higher the temperature, the lower the molecular weight of the polymer, thereby the strength of the polymer is affected. The strength of polymer is usually determined by the polymerization time set in a reasonable range because lower temperature leads to lower polymerization rate and longer time is required for complete polymerization.

Polymerization is an exothermic reaction, which exacerbates the volatilized loss of the monomer. In order to prevent the volatilized loss of monomer, polyethylene film or aluminum–platinum package can be used to wrap component up. The polymerization can also be carried out in water or steam.

Due to the volume shrink of resin during the polymerization, it is possible to generate internal stress. Therefore, the polymerized member can be heated to a temperature above the glass transition temperature of the resin for some time and then slowly cooled to remove the internal stress and to improve the strength of the product.

5.2.3.3 Performance of Impregnated Concrete

After impregnation, the performance of concrete improves significantly. Different polymer-impregnated concrete has different performance. For the concrete with high porosity and low strength, the compressive strength can be increased by four times after impregnation, the tensile strength is increased by three times, the creep is reduced by 90%, and the wear resistance is increased by 2–3 times. Water permeability can be ignored. Frost resistance and chemical resistance are greatly improved.

The studies also show that impregnation has significant effect on the concrete with high porosity and low strength, but has no obvious effect on the concrete with low porosity and high strength.

5.3 Application of Polymer Composites in Civil Engineering

The application of polymer composites in highway engineering includes polymer-fiber-reinforced concrete, fiber-reinforced polymer (FRP) concrete, cement concrete polymer admixture, waterproof agent, bridge reinforcement, concrete construction maintenance, soft rock reinforcement, and so on.

Polymer-Fiber-Reinforced Concrete

The development of polymer fiber used for concrete has been more than 20 years in the world, but it is applied with an industrial scale in recent 10 years. Because it can significantly improve the crack resistance and durability of concrete, it is known as a new breakthrough in concrete technology. The polymer fiber can be used as the primary reinforcement to improve the tensile and toughness of the concrete. It is used for making various cement boards. In the initial stage of loading, the concrete matrix is mainly subjected to external force. When the base is cracked, the fiber of the horizontal crack becomes the main bearer of the external force. It can also be used as a secondary reinforcement to improve the crack resistance of the cement concrete.

Fiber-Reinforced Polymer Concrete

The problem of steel corrosion in traditional steel-reinforced concrete structure has become increasingly prominent with time. In some areas, a large amount of deicing agent which is mainly composed of salt is scattered on the pavement and the bridge deck in winter. It causes damage to the protective layer and corrosion of the bearing steel, which accelerates the deterioration of the structural performance of the road and bridge. The salt erosion in seawater also affects the life service of cross-sea bridge structure. Factors such as acid rain formed by air and environmental pollution also exacerbate the corrosion of steel in the structure.

The application of Fiber-Reinforced Polymer (FRP) provides a practical solution to these problems so that it has received considerable attention in all aspects of bridge design and construction.

At present, FRP is mainly used in civil engineering structures in four forms: (a) replacing ordinary steel bars with FRP Rebar and tight wire; prestressed steel bars and steel strands used for various new structures and reinforcement project; (b) tubular member structure used in the new construction of concrete structure, that is, FRP shell confined concrete member or FRP tube filled with concrete as member; (c) sheet used for the reinforcement of concrete structure, masonry structure, and wood structure; and (d) full composite structure.

Fibers, such as carbon fiber, aramid fiber, glass fiber, etc, are mainly used. The polymers mainly include curing resin with normal temperature, low temperature, and high humidity environment.

Polymer Plasticizer and Tackifier

Concrete admixture has become the fifth component of concrete other four components are cement, water, sand, and stone. It plays an important role in improving the construction performance of fresh concrete, the durability of concrete, and freeze–thaw resistance. The concrete chemical admixture generally refers to a chemical substance which is added when the concrete is mixing. It is not more than 5% of the mass of the cement to improve the performance of the concrete.

(a) Polymer plasticizer

The plasticizer refers to a chemical admixture which can reduce the water consumption of the mixture and ensure the working performance of the concrete.

Commonly used polymer plasticizers include: (a) lignosulfonate, (b) naphthalenesulfonic acid formaldehyde condensate plasticizer, (c) melamine sulfonate, and (d) polycarboxylate superplasticizer.

(b) Polymer tackifier

The tackifier is an admixture which can increase the viscosity of the mash slurry, reduce the phase separation rate of the system, and finally achieve the uniformity and performance of the hardened product. The commonly used synthetic polymer tackifiers include polyvinyl alcohol, polyacrylate, etc.

Polymer for Concrete Waterproof Treatment

Waterproof agent is a kind of agent added to reduce the water absorption and water permeability of concrete and mortar. When the concrete is hardened, the concrete has capillary and void inside so that the moisture will pass through, i.e., permeability. The void of concrete can be reduced greatly with its compactness improving by using a waterproof agent, thereby improving the impermeability of the concrete. There are many types of waterproof agents, which can be divided into inorganic and organic waterproof agents according to their chemical composition. The inorganic waterproof agent includes calcium chloride, sodium silicate, zirconium, and silicic acid powder, etc. The organic waterproof agent includes fat salts, paraffin emulsion, resin emulsion, asphalt emulsion, water-soluble resin, etc. Waterproof agent is mainly used in anti-seepage and waterproofing of buildings, bridges, and tunnels.

Application of Polymer and Polymer Concrete in Reinforcement

As repairing materials, polymer and polymer concrete have the advantages of quick curing, simple construction, and high strength. Many polymer concrete repairing materials were originally designed to repair highways because the traffic in highways is fast open (a few hours). However, the application of polymers and their concrete repairing materials is not limited to highways. Polymer concrete repairing materials are mainly used in the form of mortar. Resin mortar can be used for cracks repair in various concrete structures; protection and repair of concrete surface, such as anti-wear and anticorrosion protection of industrial ground, repair and protection of pavement and bridge deck, and anti-erosion protection and structure repair of hydraulic concrete; cultural relics protection, such as surface maintenance of old buildings, repair, and protection of concrete or rock statues [3].

Ultrathin Wearing Course of Polymer Concrete

Ordinary concrete decks and parking lots are subject to the erosion of rain, especially deicing salts, requiring people to develop more durable paving materials. Polymer concrete and mortar are used as the wearing course of the bridge deck and the parking lot, which has the advantages of abrasion resistance, water resistance, and chloride ion penetration resistance, thereby preventing the freeze–thaw damage of concrete and the corrosion damage of steel bars.

According to the preparation and construction methods of polymer concrete, polymer concrete wearing course can be divided into the following four types:

(a) Ultrathin wearing course of sand filled with resin. It is formed by alternately coating the resin and paving the sand at several times. It has good impermeability and anti-sliding property. Unsaturated poly, vinyl ester resin, or epoxy resin can be used.

(b) Closed ultrathin wearing course of polymer. The construction method of wearing course is as follows:
First, the dry sand with a thickness of about 6 mm is paved on the surface of the clean concrete. Then, a layer of non-slip durable aggregate is paved on the sand and tampered with the aggregate. The resin or monomer–polymer is then sprayed onto the aggregate in two portions.

(c) Ultrathin wearing course of polymer concrete prepared on site. It is paved with polymer concrete mixed on site. The resin or monomer can be mixed with the aggregate by using a small concrete mixer or a continuous polymer concrete mixer. The mixed concrete is then paved and compacted on a clean concrete surface.

(d) Prepackaged wearing course of polymer mortar. It is a system in which the monomer and the initiator, the accelerator and the aggregate in proportion are packed, respectively, by the supplier at the factory. When each package is uniformly mixed, it can be used in the construction.

Water-saving Moisturizing Film of Controllable Polymer Material

It is a new composite material for concrete curing. Its mechanism of water absorbing and moisturizing is as follows:

The polymer material adhered to the inner film of the concrete curing film has strong water absorption and water retention. It rapidly inflates after the water absorption reaches the saturation.

Due to the strong water retention and insulation of the outer film of the curing film, a moist and warm curing environment is formed on the concrete surface coated with the curing film. As the hydration of cement continues, the free water of the internal concrete disappears so that the humidity of surface continuously decreases.

The polymer material adhered to the concrete surface can release the absorbed water to the concrete surface, which continuously penetrates into the concrete to promote cement hydration through capillary action. In addition, the insulation of outer membrane causes the temperature inside the membrane to increase, accelerating the hydration process. The early hydration products increase continuously and the continuous hydration in the later stage makes the concrete structure more compact, thereby improving the concrete strength and carbonation resistance. The use of the new concrete moisturizing curing film can solve the problems, including large water consumption of the cement concrete curing, large labor input, elaborated construction, and the high curing quality which is difficult to guarantee. At present, it has been successfully applied to concrete curing of highway cement concrete pavements, bridges, ballastless tracks of high-speed rail, concrete curing of channels and slopes in water conservancy engineering, and plants maintenance in agriculture and forestry [4, 5].

Curing agent of Polymer Cement Matrix Composites for Reinforcing Soft Rock Slope

Curing agent of polymer cement matrix composites refers to the slope-curing agent. New slope-curing agent refers to a composite material that can improve the stability of engineering slopes. It can overcome the shortcomings of single material, such as cement, fly ash, and lime.

New curing agent of polymer cement matrix composites can form a curing course with certain hydration and softening resistance on the surface of the excavated soft rock slope. The slope-curing principle of curing agent of the polymer cement composites usually includes the following four aspects: (a) bonding, (b) surface covering, (c) hydration, and (d) polymerization.

Changsha University of Science and Technology has successfully treated soft rock slopes in Zhejiang, Hunan, and Guangxi by using polymer cement matrix curing agent [6]. The main polymers include acrylic latex, silicone waterproofing agent, and seal-100R.

Geopolymer Matrix Composites for Reinforcing Soft Soil Foundation

The geopolymer is prepared by mixing steel slag, slag, high calcium fly ash, metakaolin, and alkali activator in a certain proportion. It has the advantages of high strength, small shrinkage, strong corrosion resistance, and good fluidity.

At present, it has been applied in building materials, solid nuclear waste, waste treatment and aerospace materials, polymer bricks, geopolymer decorative materials, grouting of hollow road panel, rapid repair, and emergency engineering. Changsha University of Science and Technology has successfully used geopolymer-curing agent to reinforce the soft soil foundation in Wenzhou, Zhejiang Province [7].

Emulsion Wax Curing Agent (EWCA)

The choice of EWCA was primarily determined by its curing function and bond-breaking function, with consideration of relevant standards and literature both at home and abroad, as well as requirements of the tests conducted in this research. Used for bond breaking, its solid content was no less than 25%, with the mass ratio of polymer materials to paraffin being 1:2 and a qualified film-forming property. Time of film formation refers to the required time from after spraying curing agent to splashed water forming oil bead on the surface, generally between 1 and 5 h. The time of film formation can be used to determine the minimum interval between spraying curing agent and paving the surface slabs or the time without covering the plastic film after spraying before rain. For EASS with solid content no less than 25% and the mass ratio of polymer materials to paraffin being 1:2, the application rate for spraying was specified to be 0.4 L/m^2 and no less than 0.3 L/m^2 as the minimal. The special machine was used to spray so as to ensure uniformity of spraying and to control the application rate for spraying [5, 8–10].

Exercises

1. What is the polymer material? Briefly describe the mechanical properties of polymer.
2. What are characteristics of three mechanical states of linear amorphous polymer, respectively? How are they applied in practical production?
3. Briefly describe the main factors on strength of polymer concrete.
4. The consumption of cement of polymer concrete is 300 kg/m^3. The mass of polymer emulsion is 100 kg/m^3. The solid content of polymer is 45%. What is the polymer–cement ratio? If the water–cement ratio is 0.43, how much water is added?

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Chapter 6
Functional Layer Materials of and Preventive Maintenance Materials of Pavement

6.1 Functional Layer Materials of Pavement

6.1.1 Functional Layer Materials of Cement Concrete Pavement

The design calculation theory of existing cement concrete pavement regards the surface layer as a flexible sheet placed on a continuous basis. In addition to the granular base, the granular base and the subgrade are regarded as elastic foundation with multiple layers. The top of foundation is regarded as the characterization of rebound modulus. The other types of base course should be in accordance with the separated double-deck surface course and base course. The base course below is in accordance with the elastic foundation treatment model for structural analysis. Therefore, the surface course is required to contact smoothly with a base course. That is, evenly support, closely contact and leave no gap but it is allowed to slide. Therefore, an intermediate layer or an isolation layer in the project is laid between the base course and the surface course of cement concrete.

The main functions of isolation layer are to reduce the degree of bonding between the surface layer and the base layer, to reduce the friction between the layers, to eliminate or reduce the weak transition layer of the lower surface of concrete base course in the construction, to reduce the early broken plate of cement concrete pavement, and to improve the erosion resistance of cement-stabilized material base. Some isolation layers also have a damping buffer effect [1]. The current technical specification for construction of cement concrete pavements defines the isolation layer as the seal coat, including buffer seal and isolation seal [2–8].

The buffer seal is generally set between the lean concrete base and the bottom of cement concrete pavement. The materials of buffer seal can be medium-grained asphalt concrete and fine-grained asphalt concrete according to the thickness. The thickness is determined by the design, generally 20–50 mm. The raw materials, mix proportion, and construction technology of medium-grained asphalt concrete and

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fine-grained asphalt concrete are shown in *Technical Specification for Construction of Highway Asphalt Pavements* (JTG F40).

The isolation seal is set usually between the semi-rigid base course and the bottom of cement concrete pavement. There are three kinds of isolation materials. The first one is the paving asphalt materials. That is, the emulsified asphalt slurry seal and asphalt gravel seal are used in the structure design theory and method of cement concrete pavement at home and abroad. The second one is the paving thin-layer coil materials, including laying geotextile, plastic film, linoleum, etc. The third one is the spraying emulsion materials. The isolation layer is formed after the curing. The representative material is the wax-curing agent [9, 10].

6.1.1.1 Slurry Seal

(a) **Raw Materials of Slurry Seal**

Mineral Aggregate

The aggregate for the slurry seal must match the emulsified asphalt. At the same time, it must meet the engineering requirements. The limestone as the mineral aggregate can be adopted.

The mineral grade of mineral aggregate mixture (including filler) for slurry seal meets the requirements of *Technical Guidelines for Micro-surface and Slurry Seal*. The passing rate of each sieve of mixture must fluctuate within the permissible fluctuation range of the design standard gradation, and the resulting grading curve should avoid serration.

The aggregate for the slurry seal mixture must be collected in five different locations on the aggregate stacking site. After it is mixed evenly, the mix proportion is designed. If the gradation of five sites is significantly different, the material must not be used for the construction [11].

Emulsified Asphalt

The emulsified asphalt for slurry seal should meet the relevant provisions of *Code for Construction and Acceptance of Asphalt Pavements*. The cationic slow-crack emulsified asphalt should be chosen. The standard viscosity is 12–40 s and Engler viscosity E25 should be 3–15. The main technical indices of emulsified asphalt should meet the requirements of Table 6.1.

The maximum thickness and material usage of the slurry seal are shown in Table 6.2.

Fillers

The ordinary Portland cement can be used as filler and mixed with mineral powder. Before used, it must strictly screen mesh to ensure that all pass 0.074 mm sieve. As an important part of grading of aggregate and chemical components, the type and amount of filler should be determined by the design test of mixture. Once it is determined, the deviation of consumption should not exceed ±1%.

Table 6.1 Main technical indices of emulsified asphalt

	Test items	Standard requirements	Test methods
Viscosity	Road standard viscosity $C_{25.3}$	12–40	T0621
	Engler viscosity E_{25}	3–15	T0622
Evaporation residue content	Residue content, %	≥ 55	T0651
	Penetration 25 °C, dm	45–90	T0604
	Ductility 15 °C, cm	≥ 40	T0605
	Softening point °C	>55	T0606
	Solubility,%	≥ 97.5	T0607
Remaining amount on the sieve (1.18 mm sieve), %		<0.1	T0652
Emulsion breaking speed		Low	T0658
Storage stability(1 day), %		<1	T0655

Table 6.2 Maximum thickness and material consumption of slurry seal (square aperture)

Items	Indices (middle seal coat)
Maximum thickness of seal coat after curing and molding (mm)	6.4–8.0
Consumption of dry mineral aggregate (kg/m^2)	5.4–8.1
Asphalt consumption (mass percentage of dry mineral aggregate) (%)	7.5–13.5
Consumption of filler (mass percentage of dry mineral aggregate) (%)	0–3
Total water content (mass percentage of dry mineral aggregate) (%)	12–20
Water consumption (mass percentage of dry mineral aggregate) (%)	6–11

Water

Water should be tap water or clean river water. It does not contain harmful soluble salts or substances and other pollutants which can cause chemical reactions. If the source and performance of water are unclear, we must do the test to verify.

(b) **Mixture**

The mix design test of slurry seal mixture is carried out as follows:

The mixing time of mixture is predicted by mixing test before the demulsification. The test temperature for mixing test and curing time test is the maximum temperature that may be encountered during construction.

The actual construction time of the slurry mixture is determined by the mixing test so that the mixing material has sufficient paving construction time. The water consumption is determined by consistency test.

Table 6.3 Technical indices of slurry mixture

Items	Types	Indices
Mixing time T_m (s)	High-performance slurry sealing paver	>60
	Slurry sealing paver	>120
Consistency value CV (cm)	Mechanical mixing paving	2–3
Amount of wear WTAT (g/m^2)		<800
Amount of adhesive sand LWT (g/m^2)		<600
Bonding force CT (N·cm)	Initial setting	120
	Open traffic	200

The maximum amount of asphalt is determined by the load wheel-rolling test.

The minimum amount of asphalt and the anti-flaking performance are determined by wet wheel wear test.

The technical specifications of the slurry mixture should meet the requirements of Table 6.3.

6.1.1.2 Thin Layer Coil Materials

At present, there are three kinds of thin layer coil materials, including plastic film, composite geomembrane (one piece of geotextile and one piece of geomembrane or two pieces of geotextiles and one piece of geomembrane), and composite plastic woven cloth. The concrete pavement of each traffic grade is used for the isolation seal. Technical requirements of materials are as follows [12, 13].

(a) **Plastic Film**

Quality of Appearance

- There is no bubble, stripe, perforation, rupture, break, wrinkle, etc. to affect its role.
- The impurity, crystal point, and stiff block (0.6–2.0 mm) are no more than 20 per square meter in total. Those who are more than 2.0 mm are not allowed.
- The film is rolled and stacked, winding neatly without break.

Size

The longitudinal length of finished plastic film of single volume should be 30–50 m. The specific length of volume can be determined by both supply and demand sides. The deviation of supply length should be within ±2 %. The thickness, width, and deviation of the finished plastic film should meet the requirements of *Plastics Film and Sheeting—Determination of Thickness by Mechanical Scanning* (GB/T 6672) and *Determination of Length and Width of Plastics Film and Sheeting* (GB/T 6673).

Mechanical Properties

Mechanical properties of plastic film should meet the requirements of national standards: *Plastics—Determination of Tensile Properties—Part 3: Test Conditions for Films and Sheets* (GB/T 1040.3), and *Test Method of Right-angle Tearing Performance of Plastic* (QB/T 1130).

(b) Composite Geomembrane

Quality of Appearance

The quality of appearance of composite geomembrane should meet the requirements of national standard. Each product does not allow the existence of heavy defects. The number of light defects per 200 m^2 should not exceed five ones.

Size

The size and deviation of the composite geomembrane should meet the requirements of national standard.

Physical and Mechanical Properties

The mechanical properties of the composite geomembrane should meet the requirements of national standard. The test method should be in accordance with national standard.

The composite geomembrane with different thicknesses which is resistant to hydrostatic pressure should meet the requirements of national standard. The method of testing the hydrostatic pressure should be in accordance with the provisions of *Geosynthetics—Penetration-resist property—Part 1: Determination of static hydrostatic pressure* (GB/T 19979.1).

(c) Composite Plastic Woven Cloth

Quality of Appearance

The quality of appearance of composite plastic woven cloth should meet the requirements of national standard. The test methods of quality of appearance and size be in accordance with the provisions of *Composite Plastic Woven Cloth* (QB/T 3808).

Size

The longitudinal length of composite plastic woven cloth should be 30–50 m. The specific length of volume can be determined by both supply and demand sides. The deviation of supply length should be within ±2 %. The size of composite plastic woven cloth should meet the requirements of national standard.

Mechanical Properties

The mechanical properties of composite plastic woven cloth should meet the requirements of national standard.

Anti-crack Materials of Linoleum, Fiberglass, and Geotextile

When the linoleum, fiberglass, and geotextile are used as anti-crack layer and repair base cracks. The physical properties of linoleum should be consistent with provisions of *Fiberglass-Reinforced Petroleum Bitumen Membrane* (GB/T14686) or *Glass-Cloth-Reinforced Petroleum Bitumen Membrane* JC/T84). The technical performance of fiberglass and geotextile should meet the provisions of *Technical Specifications for Application of Geosynthetics in Highway* (JTJ/T019).

6.1.1.3 Emulsion Wax-Curing Agent (EWCA)

The choice of EWCA was primarily determined by its curing function and bond-breaking function, with consideration of relevant standards and literatures both at home and abroad, as well as requirements of the tests conducted in this research. Used for bond breaking, its solid content was no less than 25%, with the mass ratio of polymer materials to paraffin being 1:2 and a qualified film-forming property. Time of film formation refers to the required time from after spraying curing agent to splashed water forming oil bead on the surface, generally between 1 and 5 h. The time of film formation can be used to determine the minimum interval between spraying curing agent and paving the surface slabs or the time without covering the plastic film after spraying before rain. For EASS with solid content no less than 25% and the mass ratio of polymer materials to paraffin being 1:2, the application rate for spraying was specified to be 0.4 L/m^2 and no less than 0.3 L/m^2 as the minimal. The special machine was used to spray so as to ensure uniformity of spraying and to control the application rate for spraying [14–17].

6.1.2 Functional Layer Materials of Asphalt Pavement

Existing design theory of asphalt pavement in China is based on multi-layer elastic continuity system theory under the action of the double circular vertical uniform load, requiring the structural layers to maintain a continuous state. The inter-layer functional layer is formed by applying asphalt material on the surface of base course and in the surface course to avoid the sliding displacement between layers and to maintain the integrity of the pavement structure. It includes seal coat, prime coat, and tack coat. The seal coat can be waterproof, absorb stress, and bear the role of temporary traffic, including the lower seal and the surface seal. The surface seal is used for preventive maintenance (shown in preventive maintenance materials of pavement). It can improve the surface service functions. The tack coat makes the surface course of pavement bond together, which is more in line with the design theory. The prime coat can strengthen the bonding between asphalt surface course and semi-rigid base course or no-bonding material base course.

6.1.2.1 Lower Seal

In order to ensure that the semi-rigid base course and the surface course of asphalt achieve continuous bonding, the moisture is prevented from the surface course of asphalt into the base course of cement-stabilized pellet. After the construction of surface course, the hot asphalt should be poured and the gravel should be spread on the surface of base course to form the lower seal.

Asphalt

The high-quality asphalt should be adopted in lower seal. Its quality should meet the technical requirements of asphalt of lower seal. Emulsified asphalt should test content of evaporated residue, infiltration of residue, ductility (25 °C), softening point, and other indices. The hot asphalt should test penetration, ductility (25 °C), softening point, and other indices.

Aggregate

The hard, clean, and dry stone aggregate without wear and impurity should be adopted in lower seal. It is composed of particles with appropriate gradation. It should meet the requirements of *Technical Specification for Construction of Highway Asphalt Pavements*, but the passing percentage of 9.5 mm must be 100% and the passing percentage of 2.36 mm is not more than 5%.

The self-inspection and sampling inspection of aggregate of lower seal should be consistent with the relevant provisions.

Construction Requirements

When the lower seal is paved, the hot asphalt should be first sprayed. The road petroleum asphalt should be consistent with that of the lower surface course. Its technical performance should be consistent with the technical standards of road petroleum asphalt.

The amount of hot asphalt for the lower seal should be determined according to the size and consumption of the chips, and the working condition of the asphalt sprayer, etc., and confirmed by the test section. The amount of hot asphalt should be controlled in the range of 0.4–0.6 kg/m^2.

The hot asphalt for the lower seal must be sprayed with asphalt sprayer in the construction. Asphalt sprayer should be automatically controlled by computer.

The lower seal should be 3–8 mm or 5–10 mm small (gravel) stone chopped by the pisolite pre-mixer. The small gravel covers about 60% area (not fully covers but evenly covers 60%; appears black).

The stone clips for the lower seal must be spread with a rubble spreader.

6.1.2.2 Prime Coat

Technical Specification for Construction of Road Asphalt Pavements (JTG F40-2004) provides that in order to make the surface course of asphalt layer and the base course of non-asphalt material bond well, petroleum asphalt, emulsified asphalt, and coal asphalt are sprayed in the base course and a thin layer with certain depth is formed and called prime coat which can penetrate the surface of base course. The surface course of asphalt is paved till the asphalt of prime coat is completely penetrated into the base course.

Main Role of Asphalt of Prime Coat

The main role of asphalt of prime coat is embodied as follows:

- It penetrates into the surface pores of base course and enhances the bonding between the base course and the surface course of asphalt.
- It helps combine the fines in the aggregate of the base surface.
- The opening space of surface of base course which has been permeated by asphalt of prime coat is filled, and thereby a waterproof layer with a certain permeable depth is formed.
- After the base course is paved, timely spraying the asphalt can reduce maintenance cost and improve maintenance quality of base course.
- Due to postponing the pavement of surface course, prime coat can provide temporary protection for the surface course to prevent damage from rainfall and temporary traffic.

Materials Selection of Prime Coat

The high permeable emulsified asphalt, liquid asphalt, or coal tar pitch should be adopted in prime coat. Its quality should meet the requirements of *Technical Specification for Construction of Highway Asphalt Pavements*. The dense asphalt of prime coat should be adopted in base course with graded sand and gravel or other pellets. The permeable thin asphalt of prime coat should be adopted in semi-rigid base with thick surface.

Due to semi-rigid base material with strong alkaline, the infiltration effect of ordinary cationic- or anionic-emulsified asphalt is poor. A layer of asphalt film is formed so that it is easy to be stuck away when transport truck and paver are working. So the high-quality cationic or non-ionic emulsified asphalt should be adopted in prime coat. Without verification, the anionic-emulsified asphalt is generally not used. The emulsified asphalt should have an appropriate consistency, but the content of asphalt should not be less than 40%. The consistency of emulsified asphalt should be determined by the test. After sprayed, it cannot flow and penetrate into the base course for over 3 mm and no asphalt film is formed on the surface. According to the characteristics of semi-rigid base of cement-stabilized pellets, the asphalt label of emulsified asphalt for permeable layer should be 70 or 90. The prime coat should be sprayed immediately after the base course is formed and not yet hardened. After the asphalt of prime coat is sprayed, its depth into base course is not less than 5 mm (semi-rigid base)–10 mm (no binder base).

The permeable effect of coal tar pitch is best, but its toxicity is also great. So the coal tar pitch is generally not recommended as the asphalt of prime coat.

The liquid asphalt is obtained by mixing gasoline, kerosene, diesel, and other diluents with petroleum asphalt. It is most commonly used as the asphalt of prime coat abroad. Its consumption is much larger than that of emulsified asphalt. AL (M)—1,2 mixed by kerosene has the best effect. It can penetrate into semi-rigid base for 5–10 mm. When kerosene dilutes base asphalt, the molten asphalt is added into the kerosene at room temperature according to the provisions of mixed proportion. After 20 min artificial mixing, it is then cycled by the asphalt pump for 5 min. If it is ground by the colloid mill, its quality is better. The purpose of using kerosene to dilute the asphalt is to reduce the viscosity of the asphalt and to facilitate the permeation. Therefore, the mix proportion of kerosene should be moderate. If the rate of kerosene is too large, the content of asphalt is lower. Even if there is sufficient depth of permeation, it cannot achieve the bonding effect of asphalt of prime coat. If the rate of kerosene is too low, the high consistency and viscosity of asphalt of prime coat are not conducive to penetrate so that it residues on the surface of base course. The softening point of residue is lower due to the kerosene so that it has an adverse effect on the binding layer. The mix proportion should be determined experimentally. It is usually easier to control the mix proportion of kerosene by detecting the viscosity index. Experiments show that when the viscosity of kerosene of diluting asphalt is 8–12 s, the permeation effect is good.

When AL(M)-2(medium-curing liquid asphalt)is adopted, the technical requirements are shown in *Technical Specification for Construction of Highway Asphalt Pavements*.

In the production, storage, and application of liquid petroleum asphalt, the whole process must maintain good ventilation and assign persons for ensuring safety. The heating temperature of the asphalt must not exceed 140 °C. The storage temperature of liquid petroleum asphalt should not exceed 50 °C.

Precautions for Construction of Asphalt of Prime Coat

Before construction, the floating ash on the surface of base course should be completely cleared to ensure that the asphalt of prime coat penetrates into a certain depth of the base so that the lower seal adheres to the base solidly.

Before the asphalt of prime coat is sprayed, artificial structures (such as curb) should be properly protected to prevent contamination.

Before the asphalt of prime coat is sprayed, the nozzle should be preheated and cleaned to ensure the uniformity of spraying the asphalt. If there is any omission, it should be promptly complemented by artificial spraying. If it is excessively sprayed, the chips or sand should be immediately spread. If necessary, it should be appropriately rolled.

In the spraying process, the amount of asphalt of prime coat should be ensured and should be arbitrarily adjusted or changed.

After the asphalt of prime coat is sprayed, the maintenance time should ensure that all diluents in the liquid asphalt evaporate and then the surface course of asphalt should be paved as soon as possible. In order to protect the asphalt of prime coat from being damaged by the transport vehicle, it is usually possible to sprinkle a layer of chips or coarse sand on it.

If it is windy or rainy, the asphalt of prime coat should not be sprayed and the thin film of base course should be timely maintained. When the wether condition is ideal, the asphalt of prime coat is then sprayed. Before the spraying, the road should be cleaned, including floating ash and mud on the surface of base course. Aggregate particles on top of base course are exposed as far as possible.

6.1.2.3 Tack Coat

Before the three-coat hot mixing and hot-laid asphalt mixture are paved on the top of pavement, the asphalt of tack coat should be layered into the surface of lower asphalt coat. Sides of curbs, rainwater inlets, and inspection wells which are in contact with the new asphalt mixture should also be coated with asphalt. The emulsified asphalt should be used for materials of tack coat. The size and quality of asphalt of tack coat should meet the requirements of the corresponding specification. The emulsified asphalt should be adopted in tack coat, which is the same as that of upper surface course, including its category and grade. The coal tar pitch or liquid asphalt diluted by diesel oil and kerosene should not be used. The category and consumption of asphalt of tack coat should be determined by trial spraying according to the category of pavement structure layer to which the asphalt mixture is adhered, generally 0.3–0.6 kg/m^2. The asphalt of tack coat should be sprayed by asphalt sprayer.

The quick breaking emulsified asphalt (PC-3) is adopted in tack coat. The technical requirements are shown in *Technical Specification for Construction of Highway Asphalt Pavements*. The base asphalt for preparing emulsified asphalt should meet the requirements of petroleum asphalt (A-70 A grade) in *Technical Specification for Construction of Highway Asphalt Pavements*. The emulsified asphalt should be stored in a vertical tank and kept properly agitated. It should not segregate, freeze, and demulsify in the storage period.

Precautions for construction of asphalt of tack coat are as follows:

- The asphalt of tack coat should be sprayed by asphalt sprayer. When spraying, the sprayer should maintain a stable spraying speed and volume. Asphalt sprayer must spray evenly within the width of spraying. The artificial brushing is adopted in curbs, rainwater inlets and inspection wells, and other local parts.
- The asphalt of tack coat should be evenly sprayed or brushed. The excessive asphalt should be scraped. The artificial spraying is used for the parts that cannot be sprayed by sprayer.

- After the asphalt of tack coat is sprayed, the surface course of asphalt should be paved immediately, but the emulsified asphalt should be paved after it is demulsified and its water is evaporated.

6.2 Preventive Maintenance Materials of Pavement

6.2.1 Preventive Maintenance Materials of Cement Concrete Pavement

Preventive maintenance measures of cement concrete pavement mainly include sealing and grouting of cracks and joints of pavement. Their materials selection and requirements are mainly introduced as follows [13].

6.2.1.1 Crack-Repairing Materials

- According to its function, crack-repairing materials can be divided into reinforcing materials and sealing materials. When the penetrating cracks occur in the cement pavement due to lack of strength, reinforcing materials should be used. When the surface cracks occur on the cement pavement due to dry shrinkage, temperature shrinkage, and other reasons but the strength of pavement structure still meets the requirements, sealing materials should be used.
- High modulus reinforcing materials for crack repairing of pavement should be adopted, such as modified epoxy resin or emulsified epoxy resin emulsion. The main technical requirements should be in accordance with specifications of Table 6.4.
- Sealing materials for crack repairing of pavement should be adopted, such as rubber asphalt and polyurethane (such as silicone, PU) grouting materials. The main technical performance should be in accordance with specifications of Table 6.5.
- Polymer Concrete Defect-repairing materials (PCR) can be not only used for repairing and reinforcing of cement pavement, but also used for water sealing of cement pavement. The main technical performance is shown in Table 6.6.

Table 6.4 Technical requirements for reinforcing materials

Performance	Technical requirements
Pouring consistency (S)	<20
Tensile strength (MPa)	≥ 5
Bonding strength (MPa)	≥ 3
Elongation at break (%)	2–5

Table 6.5 Technical requirements for sealing materials

Performance	Technical requirements
Pouring consistency (S)	<20
Tensile strength (MPa)	≥4
Bonding strength (MPa)	≥4
Elongation at break (%)	≥50

Table 6.6 Technical performance of *PCR* repairing material

Types	Viscosity (20 °C, cps)	Compressive strength (MPa)	Tensile strength (MPa)	Bonding strength (MPa)	Shrinkage (%)
PCR-I	<1.0	≥80	≥20	≥3	<1.0
PCR-II	60–120	≥60	≥15	≥3	<0.8
PCR-III	600	–	–	≥0.2	≥−200

Table 6.7 Technical performance of bar glue

Performance	Technical requirements
Viscosity (25 °C, MPa S)	200–400
Compressive strength (MPa)	≥60
Shear strength (MPa)	≥15
Bonding strength (MPa)	≥4
Drawing force resistance (φ16 mm screw-thread steel, KN)	≥20

- The adhesive for steel planting of pavement should be adopted, such as low viscosity modified epoxy resin or silicone. The main technical performance should be in accordance with specifications of Table 6.7.

6.2.1.2 Joint Sealing Materials

- Joint sealing materials for repairing cement pavement should be in accordance with specifications of *Technical Specification for Construction of Highway Asphalt Pavements* (JTG F30-2003) and *Joint Sealing Material of Cement Concrete Pavement for Highway* (JT/T203).
- The joint sealing plate for repairing cement pavement should adapt to its expansion and contraction construction. It is not deformed in the construction. The durability is good and the recovery rate of resilience is high. It also has a high corrosion resistance. The foam rubber plate or asphalt fiberboard should be adopted in the freeway and first-class highway. The technical requirements should be in accordance with specifications of Table 6.8.

Table 6.8 Technical performance of joint sealing plate

Performance	Types of joint sealing plate			Remark
	Wood	Babble	Fiber	
Compressive stress (MPa)	5–20	0.2–0.6	2–10	After absorbing water, it should not be 90% less than that of joint plate without absorbing water
Recovery rate (%)	≥55	≥90	≥65	
Extrusion volume (mm)	<5.5	<5.0	<3.0	
Bending load ((N)	100–400	0–50	5–40	

Table 6.9 Technical requirements for filler constructed in heating

Performance	Low elasticity	High elasticity
Penetration (0.1 mm)	<50	<90
Elastic recovery rate (%)	≥30	≥60
Mobility (mm)	<5	<2
Tensile capacity (−10 °C, mm)	≥10	≥15

Note Low elastic plate is suitable to be used in colder areas
Highly elastic plate is suitable to be used in hot and warm areas

- Joint sealing materials should have stronger cohesive force, high resilience, good heat resistance, and embeddedness resistance (sand and gravel), good low-temperature plasticity, good durability (wear and water resistance, antiaging), high recovery rate, and other technical performance with convenient construction. Their life is not less than 3 years. They are generally divided into heating construction joint sealing material and room temperature construction joint sealing material.
- Joint sealing material mainly constructed in heating includes SMA, PVC plaster, and modified asphalt. The resin, rubber, or modified asphalt (such as adhering band) should be primarily adopted in the freeway and first-class highway. The antiaging agent is added in the joint sealing material. The technical requirements should be in accordance with specifications of Table 6.9 and *Joint Sealing Material of Cement Concrete Pavement*.
- The room temperature construction joint sealing material mainly includes polyester (ammonia), silicone resin (such as silicone), chloroprene rubber, asphalt rubber, etc. Its technical requirements should be in accordance with specifications of Table 6.10 and *Joint Sealing Material of Cement Concrete Pavement*.
- When the joint is sealed, the shim should be used to control the joint sealing coefficient. The shim should have good elasticity, flexibility, water-absorption resistance, acid and alkali resistance, high-temperature resistance, and other performance. It includes polyethylene, polyurethane, rubber, or micro-porous foamed plastics. Its shape should be cylindrical and its diameter should be 2–5 mm larger than the width of joint. The ϕ 10–40 mm polyethylene foaming bar is generally adopted.

Table 6.10 Technical requirements for filler constructed at normal temperature

Performance	Low elasticity	High elasticity
Loss of adhesion (curing) time (h)	6–24	3–16
Elastic recovery rate (%)	>75	>90
Mobility (mm)	0	0
Tensile capacity (−10 °C, mm)	>15	>25
Bonding strength (MPa)	>0.2	>0.4
Bonding elongation (%)	>200	>400

Table 6.11 Mix proportion indices of cement slurry

Performance	Technical requirements
Water-cement ratio	≤0.55
Mobility (s)	≤140
Viscosity ($\times 10^{-3}$ Pa·s)	≤49
Bleeding (%)	≤1.0
Expansion (%)	>0.02%
3d compressive strength (MPa)	≥10

There is self-flowing density and early expansion

- When the service life of pavement is shorter, it is appropriate to use chloroprene rubber as joint sealing material. When the service life of pavement is longer (more than 10 years), it is appropriate to use silicone as joint sealing material.

6.2.1.3 Materials for Void Treatment

- The grouting materials for void treatment of plate should be adopted, such as cement mortar and cement slurry with high mobility and certain micro-expansion capacity. Its main technical performance should not only meet the specifications of Table 6.11 but also meet the following requirements:

  The curing time is moderate. The initial curing time is not earlier than 2 h and the final curing time does not exceed 3.5 h.
  The early strength is high and the compressive strength should reach 3.5 MPa after 12 h.
  The grouting materials for void treatment of plate should be adopted, such as cement mortar, cement slurry, and (emulsified) sand asphalt.

- The cement mortar for void treatment of plate is composed of cement, sand, addictive, and water. Its raw materials should meet the following requirements:

It should adopt 32.5 or 42.5 ordinary Portland cement whose performance should be consistent with specifications of *Portland Cement and Ordinary Portland Cement* (GB 175).
It should adopt the high-quality river sand (fineness modulus is less than 2.0) whose particle size is less than 3 mm(preferably less than 0.6) and mud content of sand should be less than 1%.
It should adopt rapid repairing agent with performance of water reducing, hardening, and micro-expansion for the concrete.
It should adopt clean river water or drinking water.

- The cement slurry for void treatment of plate is composed of cement, fly ash, addictive, and water. Its raw materials should meet the following requirements:

  Cement, addictive, and water should meet the above second specification.
  Fly ash should be grade II.

- The (emulsified) asphalt sand for void treatment of plate is composed of (emulsified) asphalt, sand, addictive, and water. Its raw materials should meet the following requirements:

  It should adopt quick-breaking and rapid-curing emulsified asphalt with good permeability. It can also adopt liquid asphalt (diluted asphalt). It should meet the relevant technical specifications.
  Sand, addictive, and water should meet the above second specification.

6.2.2 Preventive Maintenance Materials of Asphalt Pavement

The commonly used preventive maintenance measures of advanced asphalt pavement are mainly pre-repairing, fog seal, microsurfacing, gravel seal, paving ultrathin wearing course and thin hot mix asphalt concrete, milling and overlaying, hot in-place recycling, hot plant-mix recycling, and so on. The selection and requirements for preventive maintenance materials of advanced asphalt pavement are mainly introduced as follows [1, 13].

6.2.2.1 Fog Seal

The fog seal is a preventive maintenance technology that sprays emulsified asphalt diluents or special pavement protectors onto existing asphalt pavement. It can seal the surface layer of original asphalt pavement to improve the sealing and waterproof of pavement and to prevent the aggregate from further loosing and peeling off. At the same time, it can close the small cracks and add fresh asphalt for the aging pavement to extend the service life of pavement. The fog seal can also be used for fixing the gravel on the seal coat to prevent the vehicle from being damaged by splashing gravel.

Table 6.12 Serviceability and limitations of fog sealing construction

Serviceability	Roles
Aging and damaged pavement with rough surface and good anti-slip performance	Repair, regenerate, and protect old pavement Anti-slip reference values BPN $\geq$ 55, TD $\geq$ 0.8 mm
New paved gravel seal coat	Fix gravel and protect seal coat
Milling or grinding HMA surface	Decrease dust to prevent the aggregate from spalling
Non-serviceability	Reasons
Tight pavement	Emulsified asphalt cannot be absorbed, which results in a smooth surface
New pavement within a year	Cause pavement bleeding easily
Emulsified asphalt pavement within five years	Slightly aging
OGFC pavement	Cause drainage role reducing or losing
Low temperature (atmospheric temperature <10 °C, pavement temperature <15 °C), rainy days	Affect emulsion breaking and infiltration

After the construction of fog seal, it general takes at least 2–3 h of curing time to ensure that emulsified asphalt can be fully demulsified, and to ensure that asphalt emulsion can fully penetrate into the original pavement.

The inappropriate use of fog seal will lead to the decreased anti-skid ability and smoothness of pavement, affecting the quality of traffic. At this time, it can restore the anti-skid performance by sprinkling sand particles.

At present, the commonly used fog seal can be divided into two categories according to the materials. One is the fog seal of ordinary emulsified asphalt. Its material is the ordinary emulsified asphalt diluents which are composed of ordinary asphalt, emulsifier, and water. It can improve the conditions of pavement and can enhance the water permeability. The other is the fog seal with regenerant. Its material is petroleum emulsion with regenerant which is composed of modified asphalt and asphalt active regenerant. It can play an important role of ordinary asphalt. It can also regenerate the asphalt of aging pavement in and restore its service performance to extend the service life of pavement.

Considering the permeability and roles of fog seal materials, climatic usability, and limitations of pavement of fog seal construction are shown in Table 6.12.

Fog seal material of ordinary emulsified asphalt is usually composed of emulsified asphalt and water diluents.

The emulsified asphalt for the fog seal may be cationic-emulsified asphalt or anionic-emulsified asphalt.

Cationic-Emulsified Asphalt

Commonly used cationic slow set emulsified asphalt is CSS-1 and CSS-1 h. In some cases, CQS-1 h (and LMCQS-1 h) can be adopted, which has the fast speed of demulsification.

CSS-1 refers to cationic slow set emulsified asphalt. It is high-performance emulsified asphalt prepared with 120–150 pen binder.

CSS-1 h is also a kind of cationic slow set emulsified asphalt, but it is high-performance emulsified asphalt prepared with AR 2000 binder.

CSS-1 and CSS-1 h is specially formulated for patches of asphalt pavement. A special emulsifier is adopted to ensure that the asphalt can be well wrapped on the surface of a variety of aggregates. They can be used for fog seal, stability of base course, dust suppression, and other operations. Ordinary van and turbulent or flat nozzle can be used for spraying, which applies to all slurry equipment and micro-surface equipment.

Water matrix and non-combustible are classified as harmless products and are in line with ASTM D2397. They have no negative impact on the environment under the correct use. In the emulsified asphalt aqueous solution prepared with CSS-1 and CSS-1 h, emulsified asphalt: water = 1:1.

Anionic-Emulsified Asphalt

Commonly used anionic-emulsified asphalt is SS-1 and SS-1 h.

SS-1 refers to anionic slow set emulsified asphalt. It is high-performance anionic-emulsified asphalt prepared with 120–150 pen binder polymer modification.

SS-1 h is also a kind of anionic slow set emulsified asphalt. It is high-performance anionic-emulsified asphalt prepared with standard AR 2000 binder polymer modification.

SS-1 and SS-1 h are specially formulated for high-performance mixed grade emulsified asphalt and stabilized concrete with special emulsifiers to ensure that the asphalt can be well wrapped on the surface of a variety of aggregates. Ordinary van and turbulent or flat nozzle can be used for spraying, which applies to all slurry equipment and micro-surface equipment.

They are water matrix and non-combustible. They are classified as harmless products and are in line with ASTM D2397. They have no negative impact on the environment under the correct use. In the emulsified asphalt aqueous solution prepared with SS-1 and SS-1 h, emulsified asphalt: water = 1:3.

Fog Seal Materials with Regenerant

There are several forms of fog seal materials with regenerant that may contain asphalt, polymer-emulsified asphalt, and other additives. It can only be used in the pavement of significant aging, brittle cementation materials, and loose mixed materials.

In some cases, for special purposes, the emulsion is added with some additives. For example, adding reclaimed asphalt mixture can soften the aging cementation materials of pavement and restore their performance.

6.2.2.2 Microsurfacing Technology

The microsurfacing technology originated in Germany in the 1970s. It has now become one of the main preventive methods for advanced highways in the United States, Canada, and other areas. Since the technology was introduced into China, it has been widely promoted and applied in most of provinces and cities. *Technological Guideline of Microsurfacing and Slurry Sealing* (2006) has been initially formed.

The special machinery and equipment are adopted to pave the slurry mixture to the original pavement in microsurfacing. The slurry mixture is composed of polymer-modified emulsified asphalt, coarse aggregate, fillers, water, and additives which are mixed in accordance with the mix design. The thin layer is soon opened for the traffic with high anti-skid and durability. The opening time of microsurfacing depends on the environment in which the projects are located. The traffic can be opened within 1 h at 24 °C with the humidity of 50% (or less).

Foreign studies showed that the service life of microsurfacing is generally 4–6 years and the service life of original pavement can be generally enlarged for 3–5 years.

According to the nominal maximum particle size, the microsurfacing mixture can be divided into MS-2 and MS-3. MS-3 is used for overlay and rut filling of highway and first-class highway with the nominal maximum particle size of 9.5 mm. MS-2 is used for overlay of highway and first-class highway with the nominal maximum particle size of 4.75 mm.

Microsurfacing can only be used for pavement with good structural performance. Before it is applied, the original cracks and pits of pavement must be repaired. It can repair rut, loosing, and bleeding of pavement and significantly improve the anti-skid ability. Microsurfacing with a good grading design can be completely impermeable to block the micropores and repair the slightly cracks, thereby protecting the structure of pavement.

If the performance of raw materials is not qualified with improper grading design or low construction level, it will not only lead to too large porosity of microsurfacing mixture and loss of bleeding, but also may lead to too large running noise of micro-surface, thereby reducing the service level of pavement. It is also possible to cause the anti-skid performance of the microsurfacing mixture to decay too fast.

Too fast demulsification of modified emulsified asphalt, uncompatibility of aggregate with modified emulsified asphalt, lack of cleanliness of aggregate, and other reasons can lead to too large consistency of microsurfacing slurry mixture, resulting in segregation and scratches in the construction.

Asphalt–aggregate ratio and the amount of water without precise control will cause microsurfacing slurry mixture to loose and bleed.

The hot or cold weather is not conducive to the demulsification of slurry mixture. Therefore, it should avoid such climatic conditions. The construction should stop when it rains.

Table 6.13 Technical requirements for modified emulsified asphalt used for microsurfacing

Test items		Technical requirements	Test methods
Remaining amount on the sieve (1.18 mm sieve), (%)		≤0.1	T0652
Electric charge		Cation (+)	T0653
Engler viscosity E25		3–30	T0622
Asphalt standard viscosity C25,3, (s)		12–60	T0621
Evaporation residue content, (%)		≥60	T0651
Characteristics of evaporation residue	Penetration (100 g, 25 °C, 5 s), (0.1 mm)	40–100	T0604
	Softening point, (°C)	≥57	T0606
	Ductility (5 °C), (cm)	≥20	T0605
	Solubility (trichloroethylene), (%)	≥97.5	T0607
Storage stability	1 day, (%)	≤1	T0655

Modified Emulsified Asphalt

The modified emulsified asphalt for microsurfacing must meet the requirements of slow breaking and rapid curing. It must also meet the requirements of molding as far as possible to open traffic ensure that the slurry mixture has enough mixing time. If the emulsified asphalt demulsifies too fast, it will lead to uneven mixing of aggregate. Modified emulsified asphalt also requires sufficient storage stability to meet the requirements of longer periodic construction.

The cationic polymer modified emulsified asphalt must be adopted in microsurfacing engineering. The ratio of modifier and pure asphalt should not be less than 3%. The specific requirements for BCR are shown in Table 6.13.

Aggregate

The maximum particle size and sand equivalent of aggregate has a significant effect on the microsurfacing paving. If the maximum size of aggregate is too large, it will easily lead to scratches, pits and segregation, and so on in the construction. If the cleanliness of aggregate is poor, it will also easily lead to scratches, pits and segregation, and so on. The demulsification of emulsified asphalt will become faster.

Microsurfacing aggregate should be produced by three crushing equipment, including jaw crusher, cone crusher, and impact crusher. The screening equipment should meet requirements of gravel production. The dust removal equipment should be set in the impact crusher and vibrating screen.

Technical indices of microsurfacing coarse aggregate should meet the requirements of Table 6.14.

The aggregate for filling rut should contain two grades: 0–5 and 5–10 mm.

Table 6.14 Technical indices for coarse aggregate used for microsurfacing

Material name	Items	Standards	Test methods	Remark
Coarse aggregate	Stone crushing value (%)	≤26	T0316	–
	Los Angeles wear loss (%)	≤28	T0317	–
	Stone polished value (%) (BPN)	≥42	T0321	–
	Firmness (%)	≤12	T0314	–
	Flaky particles content (%)	≤15	T0312	–
Fine aggregate	Firmness (%)	≤12	T0340	>0.3 mm part
Synthetic mineral aggregate	Sand equivalent (%)	≥65	T0334	<4.75 mm part of synthetic mineral aggregate

The aggregate for overlay should contain three grades: 0–3, 3–5, and 5–10 mm. When conditions are limited, it can also use two grades: 0–5 and 5–10 mm.

Filler

Microsurfacing mineral aggregate can be mixed with mineral powder, cement, lime, and other fillers. The fillers should be dry, loose, and agglomerated. It should be consistent with the relevant requirements of *Technical Specification for Construction of Asphalt Pavements* (JTG F40).

The main role of mineral powder is to improve the mineral gradation. The main role of cement, lime, and other chemically active fillers are to adjust mixed time, slurry state, and molding speed of slurry mixture.

The amount of filler must be determined by the mix design test.

Additive

The main role of additives is to adjust the mixing time, demulsified speed, traffic-opening time, and other construction performances of slurry mixture. To a certain extent, they change the road service performance of mixture.

Commonly used additives include inorganic salt additives, organic additives, and so on. For cationic-emulsified asphalt mixture, inorganic salt additives generally extend the mixing time and delay the molding.

The determination of additive types and dosages is an important part of mix design. The additives should not adversely affect the road service performance of mixture.

Unapproved additives must not be used in construction.

Table 6.15 Requirements for gradation of mineral aggregate used for micro-surfacing

Types of gradation	The mass percentage of mineral aggregate through the following sieve (square aperture mm) (%)							
	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
MS-2	100	70–90	45–70	28–50	19–34	12–25	7–18	5–15
MS-3	100	70–90	45–70	28–50	19–34	12–25	7–18	5–15

Table 6.16 Requirements for technical indices of mixture used for microsurfacing

Test items	Standard
Mixing time (35 °C)	≥60 (s)
Bonding strength test (35 °C) (N·m) 30 min (initial setting time) 60 min (traffic open time)	≥1.2 ≥2.0
Adhesive sand of load wheel (g/m^2)	≤450
Wet wheel wear loss (g/m^2) Immersion for 1 h Immersion for 6 h	≤540 ≤800
Change rate of width in the test of wheel rut deformation (%)	≤5

Water

Microsurfacing water must not contain harmful soluble salts, chemically reacted substances, and other pollutants. The drinking water is generally adopted.

Mixture Requirements

Requirements, original pavement conditions, traffic, climate conditions, and other factors should be fully considered in the mix design of microsurfacing mixture. The appropriate microsurfacing method is selected and the construction plan is determined.

The grading of mineral aggregate should meet the requirements of Table 6.15.

The indoor test indices of microsurfacing mixture should meet the requirements of Table 6.16.

The standard mix proportion determined by the design should not be changed in the construction. In the production, if imported materials change, the mix aggregate should be timely adjusted. If the grading of mineral aggregate of microsurfacing mixture and technical indices of slurry mixture do not meet the requirements, it should also be timely adjusted so that the quality of slurry mixture meet the requirements and maintain a relatively stable. If necessary, the mix proportion should be redesigned.

The asphalt–aggregate ratio of mix proportion ranges from −0.3 to +0.2% of design asphalt–aggregate ratio. It is based on the design grading of mineral aggregate. The passing rate of mesh in the grading of mineral aggregate of construction mix proportion should not exceed the fluctuated range specified in specifications. If the asphalt–aggregate ratio of construction mix proportion or the adjustment of grading

Table 6.17 Requirements for gradation of ultrathin wearing course UTAC-10

Aperture size(mm)	13.2	9.5	(7.5)	4.75	2.36	1.18	0.6	0.3	0.15	0.075
UTAC-10	100	90–100	(58–70)	25–35	19–28	15–22	11–18	9–14	7–11	5–9

of mineral aggregate exceeds the above requirements, reasons must be found out as soon as possible for rectification. If it still exceeds the required range after the rectification, it must be shut down to redesigned the mix proportion.

The slurry mixture should be detected by sampling. Sampling items, frequency, allowable error, and methods meet the requirements of specifications.

6.2.2.3 Ultrathin Wearing Course

Ultrathin wearing course is a thin layer structure that hot mix asphalt mixture of gap gradation is directly paved on the tack coat of modified emulsified asphalt by special machine. Its total thickness is about 1.5–2.5 cm. It can quickly open the traffic. Its representative structures include UTAC-10 and Shell's patented product Novachip.

UTAC-10 is a thin layer structure with larger texture depth and better anti-skid performance. Requirements of *Specifications for Design of Highway Asphalt* (JTG D50-2006) for mixture gradation of UTAC-10 are shown in Table 6.17.

Requirements for raw materials and construction of UTAC-10, and its quality control methods are similar to hot mix asphalt concrete AC-13. The specific content can refer to the construction specifications. NovaChip's material requirements are introduced in this section.

NovaChip is an ultrathin wearing course formed by hot mix mixture of gap gradation of coarse aggregate and modified asphalt (Nova Binder). It is constructed by Nova Paver which is an integrated device. First, a thicker special tack coat (Nova Bond, $\approx 1.1\ \mathrm{l/m^2}$) of modified emulsified asphalt is sprayed on the old asphalt pavement, followed by paving hot mix asphalt. Then, emulsified asphalt rises and wraps around the stone of hot mix asphalt mixture. The tack coat of emulsified asphalt quickly demulsifies, which makes the ultrathin hot asphalt wearing course and the original pavement achieve full bonding, followed by rolling and molding. Its thickness is generally 10–25 mm. It takes 20 min to open the traffic.

NovaChip ultrathin wearing course can strongly adhere to the old pavement without peeling, loosing, and other diseases. Nova Bond has a good sealing effect, which effectively prevents groundwater from submerging. It also prevents groundwater from damaging the old pavement with the hydrophobic effect of mixture of gap gradation. It is convenient to construct, which has a slight effect on the traffic. The application of NovaChip is not limited by the traffic. The heavy traffic can reflect its advantages well.

As a preventive maintenance measure, ultrathin wearing course cannot improve the capacity of original pavement structure. It should be used in the original pavement with good structure performance and no structural damage. Before the construction, cracks, pits, repairing damage, and other damage must be carefully restored in the original road. If the thickness of rut is more than 1.5 cm, it should be prefilled.

Ultrathin wearing course can appropriately improve the flatness of pavement. If the flatness of pavement is relatively low, such as IRI > 2.3, ultrathin wearing course may hardly improve the flatness.

When the density of pavement crack is large, such as $20 \leq CR \leq 50$, it is necessary to install the stress-absorbing membrane and the ultrathin wearing course is then constructed.

The skeleton of NovaChip is composed of coarse aggregate. Its plaster is composed of fine aggregate and asphalt. Fillers are adopted, such as lime and cement. NovaBond is a specially waterproof tack coat of modified emulsified asphalt to seal the old pavement and ensure that the NovaChip mixture is firmly bonded to the old pavement.

Asphalt

NovaBinder asphalt and NovaBond waterproof asphalt for the NovaChip mixture are generally modified emulsified asphalt. It should meet the requirements of specifications.

Aggregate

NovaChip stone must be close to the cube. The needle-like stone must be strictly controlled. The durability of stone must be good. When NovaChip is applied to freeways and first-class highways, the indices of coarse and fine aggregates are in accordance with the relevant specifications.

Requirements for Fillers

The mineral powder ground by limestone and other hydrophobic stones should be adopted. The mineral powder must be dry and clean. It should meet the requirements of specifications.

Requirements for Mixture

There are three main gradations of NovaChip mixture, as shown in Table 6.18. Gradation A is more compact, which is used less in the general pavement and used more in the airport pavement. Gradation B is widely used. Its texture depth and friction performance are higher than those of Gradation A. Gradation C is mainly used in the large traffic pavement with larger texture depth and better friction performance.

Exercises

1. Briefly describe the main functions of isolation layer of cement concrete pavement.
2. Briefly describe the main functional layers of asphalt pavement and their roles.
3. Briefly describe commonly used preventive maintenance measures of advanced asphalt pavement.
4. What is the difference between slurry seal and microsurfacing?

Table 6.18 Requirements for gradation of NovaChip mixture

Aperture size (mm)	Gradation A		Gradation B		Gradation C	
	Passing percentage (%)	Allowable fluctuating range (±%)	Passing percentage (%)	Allowable fluctuating range (±%)	Passing percentage (%)	Allowable fluctuating range (±%)
16	100		100		100	
13.2	100		100		85–100	
9.5	100		85–100	5	60–80	5
4.75	40–50	4	28–38	4	28–38	4
2.36	22–32	3	25–32	4	25–32	4
1.18	15–25	3	15–23	3	15–23	3
0.6	10–18	3	10–18	3	10–18	3
0.3	8–13	3	8–13	3	8–13	3
0.15	6–10	2	6–10	2	6–10	2
0.075	4–7	2	4–7	2	4–7	2
Asphalt content	5.0–5.8		4.8–5.6		4.6–5.6	

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