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Review and Prospects of New Materials in Urban Underground Development

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Abstract: The main prospects of urban underground development in China are greater depths and wider dimensions for usable spaces. New materials are required in the development of advanced devices and technologies. This study summarizes the status of the main materials currently in use and the prospects for new materials from the perspective of materials for mechanical excavation, support materials, and environmental protection materials. In addition to being strong, new materials also need to be environment-friendly. Thus, the prospects of self-healing, biological, and green support materials for urban underground development are hereby demonstrated.

Keywords: urban underground space; new materials; shield tunneling; grouting; environmental protection

1 Introduction

In recent years, urban population and economics in China have been growing rapidly. To solve the attendant traffic and environmental problems, the trend is to build different kinds of underground structures such as punctiform constructions (station square, civic square and afforested square), linear constructions (metro tunnels, utility tunnels, drain tunnels), and reticular constructions [1]. Urban underground development is facing a lot of challenges such as proper choice of materials that is instrumental in deciding the progress and quality of the construction. Therefore, research on updated and effective materials is an urgent issue in urban underground development.

Urban underground environments are complicated, and the density of surrounding buildings is very high. It is difficult to simultaneously ensure the safety of constructions and avoid adversely affecting surrounding buildings during constructions. Deeper and broader urban underground development requires support from new materials. This paper first analyzes the advantages and disadvantages of current materials from three perspectives: materials used by excavation machinery, materials in retaining structures, and materials used for environmental protection. Conventional materials have several limitations, as briefly highlighted below. The cutters used in shield machines are prone to wear. Reinforced concrete shield segments are easy to produce but also easy to crush. Cement grout has high reliability but low penetrability. Chemical grout is toxic and has poor durability. Moreover, the paper summarizes the applications and trends in innovative materials such as coarse grain cemented carbide that offers great prospects for use as self-healing concrete and bio-grout. Finally, the paper summarizes the problems associated with current materials and proposes directions for the future of innovative materials that can serve as a basis for further research.

2 Materials used in excavation machinery

Shield tunneling is widely applied in the construction of ur-

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ban metro tunnels. Cutters used in tunneling boring machines (TBM) are divided into disc cutters and blade cutters. The performance and lifespan of cutters influence the efficiency of the entire tunneling process. The forms of failures associated with cutters include: wear of cutters, crack of cutter rings, damage of bearings, and separation of cemented carbide. Therefore, cutters, cutter rings, and surfacing materials are very important and need to be kept in prime shape for smooth operations.

2.1 Materials for cutter rings

TBM utilizes disc cutters to break hard rocks. In excavation process, the disc cutters receive both radial and frictional forces from the surrounding rocks. Cutter rings should have high hardness, strength, and impact resistance [2].

H13 hot die steel is the normal material used in making cutter rings, but the carbon content is usually lower than the ideal value. Zhuzhou Cemented Carbide Group Co., Ltd. produces new cutter rings made of malleable cemented carbide [3] with surface hardness of up to 60 HRC, and impact toughness equal to or greater than 15 $J\cdot cm^{-2}$. In addition, this new material has good hardenability and red hardness. The hardness of the cutter rings is distributed by grade. The outside has high hardness and wear resistance while the inside has low hardness but high toughness.

2.2 Materials for cutter heads

Cemented carbide is the normal material used in making cutters. The failures of cutters include impact failure, fatigue failure, and thermal fatigue failure. Therefore, cutters should have high thermal conductivity and low coefficient of thermal expansion to restrict the rate of growth of heating cracks and improve the fatigue resistance.

According to the grain size of wolfram carbides (WC), cemented carbides can be classified into nano grain, fine grain, and coarse grain carbides. According to the standard proposed by the Sandvik Company, Sweden, cemented carbides whose grain size is larger than 3.5 μm are classified as coarse grain size cemented carbides.

The cemented carbide applied in cutters in most advanced TBM is ultra-coarse grain size cemented carbides. Cemented carbides with coarse grain have larger stiffness, impact resistance, red hardness, and thermal conductivity than normal cemented carbides [4]. Studies show that cemented carbide has its best performance with good abrasion resistance and crushing strength when the grain size is within 3–5 μm.

2.3 Surfacing materials

Surfacing is a necessary process to prevent cutters from separating from the matrix. Normal wolfram carbide surfacing electrodes have a high WC content. Therefore, the surfacing layers are full of cracks and prone to separating from the matrix.

In the market at home and abroad, there are three primary kinds of surfacing materials that have good heat and wear resistances: cobalt-based, nickel-based, and iron-based surfacing materials. Cobalt-based and nickel-based materials have better performance than iron-based materials but are more expensive. Researchers usually improve the performance of iron-based surfacing materials by adding elements such as Cr, W, Mo, V, and Ti. Materials made by this method have a high stiffness of up to 70 HRC. Iron-based materials have good wear resistance but do not perform well at high temperatures. Ensuring that iron-based materials have good performance at 650 ℃ is still a challenge.

3 Supporting materials

Precast segment is the main lining structure in shield tunneling. Lining segments should meet the requirements of high-pressure strength, deformation resistance, seepage resistance, and long lifespan. Lining segments made of conventional reinforced concrete have the following faults [7]: ① The corners easily get spalled during handling or installing, as shown in Fig. 1 [8], ② poor crack resistance and durability, ③ poor fire resistance, and ④ low production efficiency owing to the colligation of the steel bars. In addition, conventional retaining structures consume a lot of cement that causes waste and pollution. Therefore, there is need for innovative eco-friendly materials that can help solve these problems.

3.1 Materials for precast segments

3.1.1 Fiber reinforced concrete

In fiber reinforced concrete, steel bars are replaced by steel fibers with high modulus or polypropylene fibers with low modulus.

Compared to conventional reinforced concrete, fibers increase the mechanical properties of concrete including tensile strength, bending strength, shear strength and fatigue resistance, and chemical properties including frost resistance, heat

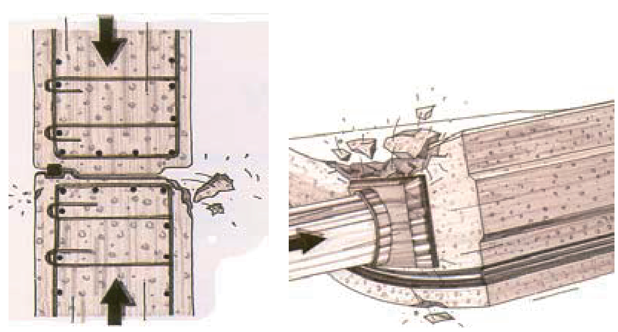

Fig. 1. Schematic diagram of damage to shield segments.

resistance and erosion resistance [9]. The fatigue resistance of steel fiber reinforced concrete is ten times that of conventional reinforced concrete [10]. Polypropylene fibers can improve the fire resistance and appearance quality of concrete. Composite fiber reinforced concrete not only has advantages in mechanical properties, but also offers economic advantages such as: ① reduce the usage of steel bars and cement, ② simplify the production process of steel bars, and ③ reduce the abrasion of equipment.

Fiber reinforced concrete has been applied in practice and achieved good results, such as in the Barcelona Metro Line 9 [11]. At home, it has been applied in Shanghai Metro Line 6 and Beijing Metro Line 10 for experimental purposes. It is worthy to promote the application of fiber reinforced concrete in engineering due to its outstanding properties and economic advantages.

3.1.2 Self-healing concrete

In recent years, researchers have proposed multiple theories about self-healing cement-based materials [12]. Up till now, there is still no uniform classification for self-healing materials. According to the mechanism of operation, self-healing materials can be classified as hollow fibers, microencapsulation, shape memory alloys, and bacteria. The first two materials (hollow fibers and microencapsulation containing some functional components) are embedded in composite matrices. When cracking takes place, the functional components will flow out and subsequently heal the cracks, as shown in Fig. 2 [13]. When the healing process is completed, the cracks get blocked and the performance of the structure recovers.

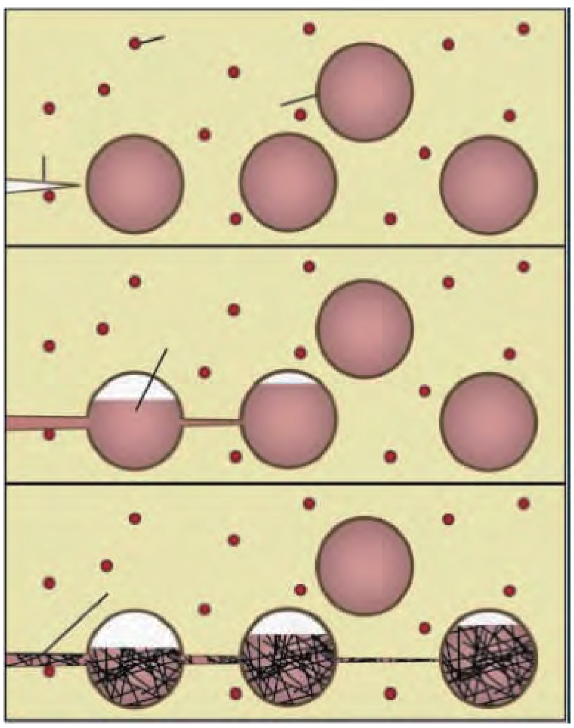

Fig. 2. Concept of self-healing using microencapsulation.

According to available research, methyl methacrylate (MMA) and silica gel are the proper materials for making the components in microencapsulation and the shell, respectively [14]. Epoxy resin or polyurethane is the proper component in hollow fibers. Hollows fibers are liable to get broken by cracks, hence hollow fibers are more effective in repairing cracks than microencapsulation. However, owing to this characteristic, it is also difficult to vibrate concrete containing hollow fibers.

Sakai et al. [15] proposed a crack-repairing system based on shape memory alloys (SMA). The basic concept is that when cracks are initiated, the shape memory materials that have shorter predefined memorized shapes than the current state will contract or shrink in a restrained condition, thereby generating a shrink force that optimally leads to the closure of the cracks. SMA can effectively restrict cracks, but the cost and requirement for working environments is very high, thereby restricting its application in the self-healing of cement-based materials [16].

The idea of bacteria-based self-healing is to utilize bacteria to promote precipitation of calcium carbonate in cracks. The most common bacteria used here are bacillus pasteurella.

There are some problems that are yet to be solved in bacteria-based self-healing such as: ① Bacteria consume calcium hydroxide to promote the precipitation of calcium carbonate. This action will reduce the pH value in concrete and erode steel bars. ② Bacteria carrier can destroy the inner structure of concrete and reduce the strength and durability. ③ Bacteria-based self-healing is not a real-time healing method and cannot deal with wide cracks. Bacteria-based self-healing is still in experimental stages and needs further research before application [17].

3.1.3 Other concrete

Self-compacting concrete can achieve good compacting effect without vibrating, owing to the existence of superplasticizers. Superplasticizers also reduce the bleeding rate of concrete that can ensure a good contact surface between a new layer and an old layer.

Self-compacting concrete mixed with fibers have the advantages of both self-compacting concrete and fiber reinforced concrete, such as good fluidity, compact resistance, tensile strength, erosion resistance, fire resistance, fatigue resistance and low bleeding rate [18,19].

3.2 Eco-friendly supporting materials

Pile-anchor support structures are very common in urban underground development. These cause large amounts of waste and pollution and affects further construction. To solve this problem, researchers and engineers have proposed many eco-friendly technologies and corresponding materials: long spiral drilled cement-soil retaining walls, combination of structural steel and recyclable anchor cable in cement-soil retaining walls, and steel-pipe support structures. These eco-friendly materials help in saving resources and protecting the environment and surrounding buildings.

4 Materials used in environmental protection

Grouting materials and waterproof materials (waterproof concrete, waterproof rolls, and waterproof coating) are commonly used to dispose the seepage problem in underground projects. Every type of conventional grouting material has some limitations: cement grouts have low penetrability, sodium silicate grouts have low setting strength, while chemical grouts are toxic and have poor durability. Waterproof materials can be classified into flexible materials and rigid materials. Flexible materials include waterproof rolls, waterproof coating, and sealing materials. The underlying principles behind waterproofing are as follows: rely heavily on prevention, combine the rigid and flexible materials, insist on multiple-protection measures, and adopt comprehensive treatment.

4.1 Grouting materials

4.1.1 Ultra-fine cement grout

Ultra-fine cement is produced by grinding common cement using the dry or wet method. The characteristics of ultra-fine cement grout are as follows [20,21]: it has good penetrability just like chemical grout and can be grouted into fine sand; it has stable suspension and a long drainage time; it has high compressive strength, early strength, good permeability resistance, and short setting time.

Ultra-fine cement grout has been researched for a long time and applied in the Three Gorges Project, but the difficulty in its carriage and high cost restrict its application in practice. Moreover, the theory behind ultra-fine cement remains to be properly studied.

4.1.2 Alkali-activated grout

Industrial waste residues can be activated by alkalis and used as materials for grouts. Compared to cement, industrial waste residues have smaller particles and better grain composition. Fly ash, mineral slag, and steel slag are common industrial waste residues.

Alkali-activated grout has high early strength and final strength, good durability, erosion resistance, permeability resistance and frost resistance. However, alkali-activated grouts are more sensitive to shrinkage than cement grouts [22].

Fly ash is cheap and easy to obtain. It is used as an additive in cement due to the fact that its components are similar to cement. The content of CaO in fly ash is insignificant. Therefore, its early strength is low and it cannot be used as binding material by itself.

The main components in slag are CaO, Al_2O_3, and SiO_2 that constitute 90% of slag. Slag has better chemical activity and smaller water consumption than common cement. According to experimental results, grout with two or three types of residues has better grain composition and final strength than grout with only one type of residue. Alkali-activated grout has better overall performance and can help in reducing the carbon emission index.

4.1.3 Bio-grout

Microbiologically induced calcium carbonate precipitation (MICP) is an innovative technique in geology engineering. The idea behind MICP is to utilize bacteria to promote the precipitation of calcium carbonate in cracks that can then strengthen the weak sand foundation.

Research on MICP is still in experimental stages. According to preliminary results, MICP can improve the rigidity, bearing capacity, and liquefaction resistance of foundations. Sandy clay treated by MICP grouting can maintain permeability to a certain extent but the ones treated by chemical grouting cannot [23]. Compared to conventional cement grouting and chemical grouting, MICP grouting has the following advantages: ① MICP grouting can influence a wide range of foundation without large pressure. Therefore, it can reduce the influence on surrounding environments. ② MICP grouting can treat poor foundations under buildings that have already been completed without any other process. ③ The MICP grouting construction period is short and the treated foundation does not need maintenance [24].

4.2 Waterproof materials

4.2.1 Waterproof rolls

There is a wide range of waterproof rolls including modified asphalt rolls and macromolecule rolls.

Modified asphalt waterproof rolls include styrene-butadiene-styrene (SBS) copolymer rolls, atactic polypropylene (APP) rolls, and styrene butadiene rubber (SBR) rolls. Macromolecule waterproof rolls include ethylene-propylene-diene monomer (EPDM) rolls, polyvinyl chloride (PVC) rolls, chlorinated polyethylene (CPE) rolls, CPE mixed with rubber rolls, ternary butadiene rubber (TBR) rolls, reclaimed rubber felts, and thermoplastic polyolefin (TPO) rolls.

Macromolecule rolls have better corrosion and ageing resistances, higher tensile strength, flexibility, and ductility compared to modified asphalt waterproof rolls.

4.2.2 Waterproof coating

(1) Spray acrylate waterproof membrane

Spray acrylate waterproof membrane is based on unsaturated carboxylate mixed with water, filler, and other additives. When mixed with the initiator by spraying, a polymerization reaction happens and a thin membrane with 2–3 mm thickness forms [25].

Spray acrylate waterproof membrane was first proposed by Japanese researchers in the 1980s. Afterwards, researchers in

America, Germany, and Canada began to study it but it was still in experimental stages. Since 2005, researchers at the Southwest Jiaotong University in China have made advances in spray acrylate waterproof membrane and applied it to some engineering projects [26].

Spray acrylate waterproof coating overcomes the faults of conventional waterproof systems. It can fit the concrete or rocks and block cracks perfectly. It can achieve very good waterproofing effect in a short construction period. However, it shows poor performance in strongly alkaline environments, thus, the fillers used in it require further research [27].

(2) Spray polyurea waterproof coating

Spray polyurea waterproof coating offers the following advantages over conventional waterproof materials [28]: fast curing, insensitivity to humidity, good ageing resistance, high tensile strength and elongation, dense surface and eco-friendliness.

On account of these advantages, spray polyurea waterproof coating is very suitable for construction and maintenance of underground tunnels [29]. But it still has some disadvantages such as poor adhesive property and bubbles in the surface layer.

(3) Cementitious capillary crystalline waterproof coating

Cementitious capillary crystalline waterproof coating is a kind of rigid waterproofing material. The base materials used in cementitious capillary crystalline waterproof coating are Portland cement or ordinary Portland cement and silica sand. Other constituent materials are some active chemistry substances, fillers, and additives. When mixed with water, the active chemistry substances infiltrate the concrete and form a crystalline structure that can fill the cracks and make the concrete impermeable [30].

The waterproofing function of cementitious capillary crystalline waterproof coating arises from two actions: filling the cracks and reducing the surface shrinkage. In addition, it has other advantages including: good water pressure resistance, erosion resistance, large depth of penetration, long effective period, and non-toxicity [31]. Cementitious capillary crystalline waterproof coating can function as a waterproof layer alone or be combined with other waterproofing materials.

It has been applied in many engineering projects and shows high effectiveness. However, it depends on import and needs further research.

4.3 Noise reduction materials

Most urban underground spaces are semi-enclosed such as metro and highway tunnels. The noise emitted from vehicles and tunnel fans forms a reverberation sound field through reflection. This phenomenon can disturb the passengers in underground space and causes severe noise pollution to the surrounding environments. Noise-reduction materials can be divided into sound-insulating materials and sound-absorbing materials. In semi-enclosed spaces, sound-insulating materials can deteriorate the noisy environment. Thus, a three-dimensional system made of sound-absorbing materials is suitable for urban underground spaces. According to the theory of sound absorption, sound-absorbing materials can be classified into porous sound-absorbing and resonance sound-absorbing materials.

4.3.1 Porous sound-absorbing materials

The theory behind porous sound-absorbing materials is this: when sound waves come in contacts with materials, the air in the material pores vibrates and the viscous force between the air and the materials converts the acoustic energy into heat. In recent years, eco-friendly and composite porous sound-absorbing materials have become main research interests.

Zhu et al. [32] established a sound-absorbing system between rails that utilizes haydite concrete. Experiments show that the system can reduce the noise volume by 4–5 dB and is effective in a wide range of frequency bands.

Wei [33] utilized open grade friction course (OGFC) in low-noise asphalt pavements and obtained a noise reduction coefficient of 0.45 by standing wave pipe method and reverberation chamber method. The low-noise asphalt pavement can reduce the volume by 6.79 dB.

Li et al. [34] used steel slag as base and mixed fly ash and silica fume with the base to produce sound-absorbing materials. This material is highly effective in sound absorption within the range of 630–1600 Hz.

Guo [35] studied the effects of pottery sand and expanded perlite with different grain sizes on sound absorption in cement-based materials. The study showed that materials made of pottery sand have a high noise reduction coefficient of 0.85 in the range of 800–1200 Hz that is the range of traffic noise. Furthermore, materials made of pottery sand offer high pressure, strength, and durability.

4.3.2 Resonance sound-absorbing materials

The theory behind resonance sound-absorbing materials is: when materials vibrate through the stimulation of sound waves, the inner friction and the friction between the materials and air molecules converts acoustic energy into heat. Common resonance sound-absorbing materials include wavy sound-absorbing boards, porous aluminum alloy sound-absorbing boards, aluminum fiber sound-absorbing boards, combination of non-woven fabric, and aluminum alloy sound-absorbing boards. These sound-absorbing boards can reduce the noise volume by 8–15 dB [36], and have been widely applied in the metro engineering projects of Nanjing, Beijing, and other cities. Optimizing the structure and combination of resonance sound-absorbing materials is a burning research interest.

5 Summary and future work

Urban underground development relies on design methods and construction techniques. Rapid urban underground development can also be promoted by research into innovative materials (green, eco-friendly, efficient, economical). As noted above, current materials applied in engineering projects still have some limitations. The primary problems are summarized as follows:

(1) The strength, durability, and combination form of current cutters need to be improved. Wearing resistance and working performance of welding materials also need to be improved.

(2) Conventional concrete lining segments has low crack resistance, poor durability, and low production efficiency. New materials such as self-healing concrete are still in research and currently lack practical applications.

(3) A lot of concrete used in retaining structures produces waste and causes environmental pollution.

(4) Each type of conventional grouting material has some limitation: cement grout has low penetrability, sodium silicate grout has low setting strength, and chemical grout is toxic and has poor durability.

(5) Waterproofing and noise-reduction materials require further development and uniform choice principles.

To solve these problems above, this paper proposes the following future directions for materials in urban underground development:

(1) Further research into cutters with high strength and durability. Improve the production technique, optimize the choice standards, and increase the percentage of homemade parts.

(2) Promote the development of self-healing materials that can restrict cracks and reduce the cost of maintenance. Emphasize further research on choice of self-healing components and shell materials, control of cracks, mix proportion and assessment of the effectiveness of healing.

(3) Promote the application of eco-friendly materials. Reduce the usage rate of cement and increase the usage rate of recyclable steel. Insist on the following principles: water-saving, resource-saving, land-saving, energy-saving, and environmental protection.

(4) Promote the application of materials for environmental protection. Noise pollution, groundwater seepage, ground surface settlement, and the mutual effects of construction on the environment are crucial problems in urban underground development. It is important to choose proper grouting, waterproofing, and noise-reduction materials.

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