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ADVANCED HIGH-PERFORMANCE MATERIALS FOR HIGHWAY APPLICATIONS

A REPORT ON THE STATE OF TECHNOLOGY

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16. Abstract:

This report reviews new and improved highway construction materials and technologies, identifying materials that can improve highway performance, replace scarce or unavailable natural materials, and contribute to more sustainable highways. The materials and processes identified have all either been introduced within the past 5 years and are not yet widely used or are still in development. They included advances in cements, concretes, asphalt binders, asphalts, metallics and polymers, aggregates, and other materials. Also included are materials that reduce noise, improve smoothness, allow for faster placement and shorter construction times, reduce energy consumption, capture CO_2, and lower costs. For each material, the report provides a description, applications, benefits, costs, current status, and sources of additional information.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1—INTRODUCTION

INTRODUCTION

This report presents a review of the availability of advanced construction materials that show promise for routine pavement construction and rehabilitation on the Federal-Aid Highway System. The Federal-Aid Highway System includes over 200,000 mi (321,868 km) of interstate and primary highway system in all 50 States, the District of Columbia, and U.S. territories. The highway pavements on this system consist of asphalt pavements (also referred to as asphalt concrete [AC] or flexible pavement) and concrete pavements (also referred to as portland cement concrete [PCC] or rigid pavements). The pavement type denotes the material used for the surface layer, the wearing course of the pavement. Each pavement type is built up of layers, starting with the existing subgrade with each successive layer utilizing better quality material.

The most costly layers and the layers that are designed and constructed to be the most durable layers are the surface layers—consisting of AC or PCC.

The generic composition of typical AC is as follows:

- Asphalt binder—6 to 8 percent by volume.
- Aggregate (graded)—85 to 90 percent by volume.
- Filler material—2 to 3 percent by volume.
- Air—2 to 4 percent by volume.

One lane-mile (1.6 lane-kilometers) of AC pavement construction can require about 2,400 T (2,177 t) of AC for a surface layer that is 6 in. (150 mm) thick.

The generic composition of typical PCC is as follows:

- Cementitious materials (portland cement, fly ash, slag)—10 to 14 percent by volume.
- Aggregate (coarse, intermediate, fine)—62 to 68 percent by volume.
- Water—14 to 18 percent by volume.
- Air—4 to 8 percent by volume.
- Admixtures—very small amounts.

One lane-mile of PCC pavement can require about 4,800 T (4,354 t) of concrete for a surface layer that is 12 in. (300 mm) thick. Also, 1 lane-mile of continuously reinforced concrete pavement (CRCP) can require about 100 to 120 T (91 to 109 t) of steel. In U.S. northern and coastal areas, the steel in CRCPs and the steel used at joints in jointed concrete pavement need to be protected to minimize the potential for corrosion that can lead to early failures of CRCPs and jointed pavements.

As indicated, every year large amounts of aggregate materials and manufactured materials are needed to support highway construction and rehabilitation in the United States. However, the poor availability of good-quality aggregates in many parts of the country and the increasing financial and societal costs to produce the needed manufactured materials are creating a concern for planners and engineers. It is, therefore, important that new and improved sources of highway construction materials be developed that will result in improved performance of the highway system, be cost-effective, and incorporate sustainable technologies. Sustainability consideration in highway construction and rehabilitation is of recent origin. However, its impact on the well-being of the Nation's highway infrastructure cannot be underestimated, as discussed next.

SUSTAINABILITY AND AVAILABILITY OF SOUND MATERIALS—A NATIONAL CONCERN

In many parts of the United States, supply of acceptable quality aggregates is very limited and aggregates are imported from neighboring States, Canada, or Mexico. In addition, the production of portland cement is very energy intensive and also accounts for high carbon dioxide (CO_2) emissions. Expectations for the future are that restrictions will be placed on cement production and the cost of cement production will rise to meet environmental regulations. Similarly, the availability of asphaltic binders is dependent on the supply of oil and oil industry efforts to maximize use of oil refining by-products. As a result, it is expected that the cost of asphalt binders of highway pavement grade will remain high, and the supply is expected to be inadequate to meet U.S. demand.

Cost of construction materials continues to increase every year. In addition, use of marginal materials results in early development of pavement distress, requiring more frequent repairs and rehabilitation and associated lane closures and traffic congestion in high-volume traffic areas. Traffic congestion also increases the potential for construction-zone accidents and increased levels of environmental pollution related to automobile emissions. Therefore, there is a strong desire in the United States to optimize the use of materials currently used for highway pavement construction and to seek advanced materials that are cheaper, better performing, and less damaging to the environment.

NEEDS FOR ADVANCED HIGH-PERFORMANCE MATERIALS

The needs for seeking advanced highway construction materials include:

- Reduced costs—get more lane-miles constructed or rehabilitated for a given constrained budget.
- Conservation of resources—support national efforts to create sustainable solutions to minimize impact of construction on the environment.
- Reduced ecological footprint.
- Extended service life.
- Optimized use of locally available materials.
- Achieving environmental benefits—reduced carbon footprint, reduced congestion-related emissions.
- Reduced work zone–related traffic delays and safety concerns—use materials that reduce the potential for early failures.

HISTORICAL EVOLUTION OF HIGHWAY CONSTRUCTION MATERIALS

Today, the U.S. Federal-Aid Highway System consists of the original Interstate Highway System and the U.S. Primary Highway System, totaling over 200,000 mi (321,869 km). The pavements along this system have undergone one or more cycles of rehabilitation or reconstruction. The

U.S. Federal-Aid Highway System is one of the best highway systems in the world and provides for efficient movement of people, goods, and services very cost-effectively. However, due to the ever-increasing traffic and environmental damage, thousands of miles of the system require rehabilitation or reconstruction every year. In recent years, over $30 billion has been spent annually for the reconstruction, rehabilitation, and maintenance of the Federal-Aid Highway System. Traffic volumes have increased significantly in most metropolitan areas with some urban highways carrying in excess of 200,000 vehicles per day.

The high volumes of traffic, limited availability of funds for highway improvement, diminishing raw materials, and concerns related to the environmental impact of construction and of poorly performing highways necessitate an urgent evaluation of technologies to improve the performance of Federal-Aid Highway System pavements by ensuring that pavements are longer lasting, smoother, safer, and environmentally friendly.

The currently used materials for pavement construction can be classified as follows:

1. Natural (Raw) Materials.
    a. Aggregates.
    b. Lake asphalt.
    c. Natural resins.
2. Manufactured (Processed) Materials.
    a. Metallic materials (steel, aluminum, zinc).
    b. Ceramic-based materials (portland cement, natural pozzolans).
    c. Visco-elastic materials (AC).
    d. Industrial by-product materials (fly ash, slag, silica fume).
    e. Other waste products (crumb rubber).
    f. Chemical admixtures for concrete.
    g. Fillers for AC.
    h. Epoxies and polymers.
    i. Fibers and fiber-reinforced polymers.
    j. Synthetic aggregates—typically, lightweight and slag aggregates.
3. Composite Manufactured Materials
    a. PCC.
    b. AC.
    c. Coated or clad steels.

This white paper reviews the availability of advanced construction materials for highway application to improve or replace the above-listed, conventionally used construction materials. These advanced construction materials can be categorized as follows:

1. New/Innovative materials to replace current materials.
2. New/Innovative materials that are less expensive.
3. New/Innovative materials that result in longer service life.
4. New/Innovative materials that result in sustainable solutions.
5. New/Innovative materials that improve the properties of marginal materials.
6. Waste and recycled materials that are optimized for use.

The criteria for including specific advanced construction materials in this white paper include the following:

1. The materials were recently introduced (have been less than 5 years in the marketplace) and are not widely used.
2. The materials are under development.

The advanced materials identified include the following:

1. Cementitious Materials.
    a. Performance-specified cements.
    b. Next-generation sustainable cements.
    c. Eco-friendly cements.
    d. Energetically modified cement.

2. Concrete Materials.
    a. Engineered cement composites (ECCs).
    b. Titanium dioxide–modified concrete.
    c. Pervious concrete.
    d. Self-consolidating concrete.
    e. Sulfur concrete.
    f. Autoclaved aerated concrete.
    g. Geopolymer concrete.
    h. Hydrophobic concrete.
    i. Ductile concrete.

3. Asphalt Binder Materials.
    a. Sulfur-extended asphalt.
    b. Bio-derived asphalt binders.
    c. High modified asphalt binders.

4. AC Materials.
    a. Warm asphalt mixtures.
    b. Perpetual asphalt pavement systems.
    c. Porous asphalt pavement.
    d. Recycled asphalt shingles.

5. Metallic and Polymer Materials.
    a. Vitreous ceramic coatings for reinforcing steel.
    b. Fiber-reinforced polymer bars for CRCPs.
    c. Fiber-reinforced polymer dowel bars.
    d. Zinc-clad dowel bars.
    e. Microcomposite steel for dowels and tie bars.

6. Aggregate Materials.
    a. Synthetic aggregates.
    b. Manufactured aggregate using captured CO_2.
    c. Materials that allow internal concrete curing.

7. Other Materials.
    a. Ultra-thin bonded wearing course.
    b. Advanced curing material.
    c. Workability-retaining admixture.
    d. Concrete surface sealers.

SUMMARY

In the United States, there has been continuous interest and effort in developing improved highway construction materials. Until recently, the development of improved materials was focused at improving specific properties of locally available materials by using additives (admixtures, extenders, modifiers). There was no strong impetus to seriously consider replacing conventional construction materials with new materials. However, it has now been recognized that the age of limitless construction materials and the use of conventional materials in their present form is fast coming to an end, and new technologies need to be developed to continue to support the rehabilitation and reconstruction of pavements along the Nation’s highway system. Today, concerns about limited availability and sustainability are driving the search for new and advanced materials for highway construction.

CHAPTER 2—CANDIDATE CEMENTITIOUS MATERIALS

PERFORMANCE-SPECIFIED CEMENTS

Description

As sustainability becomes an increasingly important element in the design and construction of transportation infrastructure, approaches are continually being sought to reduce the environmental footprint of concrete, which is the most widely used construction material in the world. Although portland cement (ASTM C150) is a relatively minor constituent in concrete, it is responsible for 90 to 95 percent of the CO_2 associated with concrete (Van Dam and Taylor 2009). The key to reducing the carbon footprint of concrete is therefore to reduce the amount of portland cement used, and one way of accomplishing that is through the use of alternative cement binders.

The recent adoption of ASTM C1157, *Performance Specification for Hydraulic Cement* (the first version of ASTM C1157 appeared in 2000), represents an important development in this area. Other portland cement specifications (both ASTM C150 and C595) are largely prescriptive, in that they are based on measured chemical and physical properties that are assumed to relate to the performance of the cement in concrete. In contrast, ASTM C1157 simply requires that the cement meet physical performance test requirements. Under this specification, six cement types are available:

- GU (general use).
- LH (low heat of hydration).
- MH (moderate heat of hydration).
- HE (high early strength).
- MS (moderate sulfate resistance).
- HS (high sulfate resistance).

For example, Type MS and HS cements use ASTM C1012, *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, to ensure resistance to sulfate attack. The performance classification of hydraulic cement is thus based on the concept that direct material performance is of interest and not its composition. This approach promotes innovative development of composite portland cements (for example, portland cement blended with limestone or multiple supplementary cementitious materials) as well as opening the door to non-portland cement binders that have the potential to significantly alter the CO_2 associated with concrete construction.

As it is a relatively new specification, the acceptance of ASTM C1157 cements is currently mixed. Although the majority of States allow ASTM C1157 cements in their building codes, only a few State departments of transportation (DOTs)—for example, Colorado, Montana, New Mexico, and Utah—accept their use for transportation projects. In time, the use of ASTM C1157 cements has the potential to lower the carbon footprint of concrete significantly while more effectively addressing the specific performance needs of transportation projects.

Applications

ASTM C1157, as an alternative to conventional portland cement (ASTM C150) and blended portland cement (ASTM C595), can be used in virtually any transportation application, including highway and airport pavements, bridges, port and loading facilities, and parking lots.

Benefits

The adoption of ASTM C1157, performance-specified cements will increase innovation in producing more environmentally benign cements specifically linked to performance.

Costs

Costs are comparable to ASTM C150 and ASTM C595 cements.

Current Status

The use of ASTM C1157 is being implemented on a small number of projects to evaluate its effectiveness. The Colorado DOT has been a leader in the use of performance-specified cements and has used them on a number of highway projects.

For More Information

Van Dam, T. J., B. W. Smartz, and T. S. Laker. 2010. "Use of Performance Cements (ASTM C1157) in Colorado and Utah: Laboratory Durability Testing and Case Studies," *Proceedings of the International Conference on Sustainable Concrete Pavements: Practices, Challenges, and Directions* (pp. 163–177), held in Sacramento, California, September 15–17, 2010. Federal Highway Administration.

Van Dam, T., and P. Taylor. 2009. *Building Sustainable Pavements with Concrete.* Briefing Document, CP Road Map Track 13: Concrete Pavement Sustainability. National Concrete Pavement Technology Center, Iowa State University. Ames, IA.

NEXT-GENERATION SUSTAINABLE CEMENTS

Description

As sustainability becomes an increasingly important element in the design and construction of transportation infrastructure, approaches are continually being sought to reduce the environmental footprint of concrete, which is the most widely used construction material in the world. As stated earlier, although portland cement (ASTM C150) is a relatively minor constituent in concrete, it is responsible for 90 to 95 percent of the CO_2 associated with concrete (Van Dam and Taylor 2009). The key to reducing the carbon footprint of concrete is therefore to reduce the amount of portland cement used, and one way of accomplishing that is through the use of next-generation cement binders that significantly reduce CO_2 emissions. Additionally, some research is underway to develop cements that actually sequester CO_2.

The recently constructed I-35W bridge in Minneapolis, Minnesota, is a real-life example of how innovation can result in a superior performing concrete while at the same time significantly reducing the carbon footprint of the structure. The bridge piers were constructed of a cementitious blend that was only 15 percent ASTM C150 portland cement; 85 percent of the blend was ASTM C989 slag cement, a co-product of the iron blast furnace (ACI 2009). Not only was this a durable concrete with a low heat of hydration, it was estimated to have an equivalent CO_2 footprint of 85 lbs of CO_2 per yd^3 (50.4 kg/m^3) compared to 527 lbs CO_2/yd^3 (312.7 kg/m^3) for a typical 6-sack (564 lbs cement/yd^3 [334.6 kg/m^3]) concrete mixture.

Recently, the potential use of alkali-activated cements and geopolymers in concrete has been gaining popularity. Alkali-activated cements do not rely on ASTM C150 portland cement, instead using alkali-activators to stimulate hydration of fly ash, slag cements, and natural materials, with the result being a durable, environmentally friendly binder. Similarly, geopolymers use alkali solutions to dissolve and then polymerize reactive minerals rich in alumino-silcate glass (e.g,. Class F fly ash, metakoalin) in a nonhydration reaction. Both alkali-activated and geopolymer cements have been used in a number of structures, but have not seen much use in the transportation field, although they are the basis for some high-early-strength patching materials. Nevertheless, numerous studies are underway or have been recently completed evaluating the possibility of using alkali-activated and geopolymer cements in transportation infrastructure, and it is likely that broader use of these materials will occur within the next few years. See the discussion on geopolymer concrete in Chapter 3.

As interest grows in reducing the carbon footprint of concrete, another research area is looking into the development of cements that actually sequester CO_2 from the atmosphere. A few different processes are under investigation. One focuses on passing CO_2-laden exhaust gases from coal-fired power plants through seawater, brackish water, or water laden with suitable minerals, resulting in a reaction between the CO_2 and calcium or magnesium ions in the water. Some companies are proposing to use this technique to produce synthetic aggregate, whereas others have proposed a process that will produce carbon-sequestering cement (Bullis 2009).

Researchers at CCS Materials, Inc. (Allen 2009) are developing CO_2-negative cements and concretes that incorporate CO_2 in their structure. The new materials have as good or better physical properties (compressive strength exceeding 14,500 lbf/in_2 [100 MPa]) than most PCCs, and they avoid chemical reactions such as alkali–silica reaction (ASR) that cause PCCs to deteriorate because the new materials are not based on hydrate chemistry and do not release hydroxyl anions that can react with soluble alkali ions to initiate ASR. Another advantage is that the new CO_2-negative concrete fully hardens in hours in contrast to portland cement, where the hydration reaction takes months to years to reach completion. To date, usable quantities of carbon-sequestering cements have yet to be produced, but it seems in time the technical hurdles that remain will be overcome, and true “green” cements will be available for use in the construction of transportation facilities.

Applications

As an emerging technology, this family of next-generation sustainable cements is still in the development stage. But it is likely that within a few years, alkali-activated and geopolymer cements will be used to create low-carbon-footprint concrete for use in transportation applications. And once carbon-neutral and carbon-sequestering cements become available, it is easy to envision widespread application in transportation infrastructure, particularly in urban environments where economic incentives through local legislation exist to reduce the carbon footprint of infrastructure.

Benefits

Once fully developed, next-generation sustainable cements will significantly reduce the carbon-footprint of the built environment. This could have significant global impact as a way to mitigate the long-term effects of global climate change.

Costs

No cost data are currently available for this next generation of sustainable cements.

Current Status

These next generations of cements are in various stages of development. Alkali-activated and geopolymer cements are already being used on a limited basis and will likely see more extensive use within the next 5 years. Carbon-sequestering cements are likely 5 to 10 years from being commercially available.

For More Information

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ECO-FRIENDLY CEMENTS FOR CONCRETE MIXTURES

Description

Eco-friendly cements are newly developed cement types that are more ecologically friendly than ordinary portland cement. Primarily, these cements are capable of reducing the amount of greenhouse gas (CO_2) emissions associated with their production, but they are also capable of sequestering and using additional CO_2 as part of the curing/hardening process that concrete mixtures undergo.

Eco-Cement is a brand-name for a type of cement that blends reactive magnesia, conventional hydraulic cement, and pozzolans and industrial by-products to reduce the environmental impact relative to conventional cement (TecEco 2009). Typically about half of the traditional cement raw materials are replaced with ash and other solid waste by-products. The resultant product absorbs CO_2, with absorption varying with the degree of porosity and the amount of magnesia (FHWA 2005). Moreover, the reactive magnesia in Eco-Cement uses a lower kiln temperature (about 750 °C [1382 °F]), whereas conventional PCC requires a kiln temperature of around 1450 °C [2642 °F]), which reduces energy requirements and hence fossil fuel usage and CO_2 emissions (TecEco 2009). Eco-Cement has the following characteristics (FHWA 2005):

- Rapid hardening, similar to high-early-strength cement.
- Short initial setting time (approximately 20 to 40 minutes).
- Handling time that can be adjusted to suit particular applications.

Two other eco-friendly cements with potential highway application are Novacem© and super-critically carbonated calcareous composites (SC^4). Novacem© is a patent-pending cement that uses a different raw material than portland cement (magnesium silicate instead of calcium carbonate [limestone]), which requires a lower heating temperature: 700 °F vs. 1,450 °F (371.1°C vs. 787.8°C) for ordinary portland cement. The lower heating temperature results in less energy used and less CO_2 released into the atmosphere. Novacem's carbon negative cement is based on magnesium oxide, and no carbon is released from the magnesium silicate raw material used. Novacem© is also capable of absorbing large amounts of CO_2 (from the air) as it cures when used in concrete mixes (Jha 2008). As a combined result of these two phenomena, the material can be considered "carbon negative."

SC^4 is a very new technology being developed in the United Kingdom (U.K.) (EPSRC 2010). While the treatment of cementitious materials with gaseous CO_2 to achieve rapid strength development has been studied for many years, treatment with super-critical CO_2 (CO_2 at 74 bar pressure and >31 °C [87.8 °F] temperature) can fully carbonate the materials through its dual liquid/gaseous state. The supercritical treatment uses greater amounts of CO_2 and, as a result of full and accelerated carbonation reactions, results in significantly increased strength and reduced permeability (University of Warwick 2010). The supercritical carbonation method is typically completed in a few hours.

Applications

Eco-friendly cements can be used in virtually any application where conventional concrete is used, including pavements, parking lots, bridges, and other structures. As emerging technologies, Novacem©, SC^4, and other similar cement types must continue to undergo testing and evaluation before formal use in the highways arena. Initial applications of Novacem© are expected to be for decorative and other non-load-bearing concretes (Jha 2008). Several years of testing will be required to ensure the material is strong enough for load-bearing applications, such as buildings, roads, and bridge structures. While SC^4 appears to have great potential for load-bearing applications, its use with reinforcing steel could be limited since the carbonation can be detrimental to the steel (i.e., increased rust formation). A thick cover layer of plain concrete around the steel would be needed to prevent the carbonation reaction from reaching the steel.

Benefits

The primary benefits associated with the use of eco-friendly cements are their sustainability features and overall environmental friendliness. They incorporate solid waste and sewage sludge, can be produced at lower kiln temperatures, and also absorb and sequester CO_2, while also possessing rapid-hardening abilities. Once fully developed, ecological cements like Novacem© and SC^4 will significantly reduce the carbon footprint of the built environment. In addition, other eco-cements that incorporate waste materials will help reduce landfill requirements and the energy and CO_2 emissions associated with hauling wastes. Lastly, it is expected that the improved strength and permeability properties of SC^4 will greatly improve the longevity of concrete structures and pavements, thus increasing the sustainability of infrastructure.

Costs

No information is currently available on the costs of the newly developed eco-friendly cements.

Current Status

Research on the development and use of eco-friendly cement continues, with considerable work being done in Australia, Japan, and Great Britain. The latest indication for Novacem© is that an operational pilot plant for producing the material in the U.K. is expected in 2010 (Novacem 2008), and, if all goes well, the cement might be on the market within a few years (Jha 2008). The development of SC^4 is not as far along, with major research still being conducted by a collaboration of U.K. universities and industrial partners (University of Warwick 2010).

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ENERGETICALLY MODIFIED CEMENT

Description

Energetically modified cement (EMC) is produced through a patented process of high intensive grinding of portland cement together with pozzolans (Jonasson and Ronin 2005). By intensively grinding and activating the cement with the pozzolans, the surfaces of the pozzolans are activated, which creates a network of sub-microcracks, microdefects, and dislocations in the particles that allow deeper water penetration, thereby increasing the binding capacity of the cement (FHWA 2005). This not only helps increase the rate of strength gain (which can be a problem with traditional blended cements) but also translates into lower cement requirements, which means less energy usage and suggests improved longevity and durability.

Applications

EMC has the potential for use in nearly any type of application, including bridges, foundations, pavements, container facilities, and warehouse floors.

Benefits

EMC cement is noted to provide the following benefits (Klemens 2004):

- Reduced cement requirements.
- Increased set times.
- Increased strength.
- Improved durability.
- Improved workability, finishability, and pumpability.
- Reduced shrinkage.

Costs

No information is available on the costs of EMC.

Current Status

EMC has undergone over 15 years of research and development in Sweden, where it has been used in bridges, foundations, and road construction. A plant was constructed in Texas in 2004 to produce a more reactive fly ash (CemPozz®) using the same Swedish patented technology used to produce EMC (Klemens 2004). The Texas and Pennsylvania DOTs have included CemPozz® in their specifications for paving and structural concrete, allowing up to 50 percent replacement of portland cement.

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CHAPTER 3—CANDIDATE CONCRETE MATERIALS

ENGINEERED CEMENT COMPOSITES

Description

ECCs are high-performance, fiber-reinforced cement-based materials. ECCs are similar to conventional fiber-reinforced concrete (FRC) in terms of its constituent materials, except coarse aggregates are not used (these adversely affect the ductile behavior of the material) and lower fiber contents are employed (typically 2 percent or less by volume) (Li 2005). Furthermore, unlike FRC, ECC is a micromechanically designed material, which means that the mechanical interactions between the fiber, cement matrix, and interface are taken into account by a micromechanical model which relates these individual constituent properties to an overall composite response (Li 2005). The end result is a highly ductile composite material nicknamed "bendable" concrete by many researchers.

Some of the characteristics of ECC materials include the following (Li 2005; Yang et al. 2009; PCA 2009):

- High tensile ductility (strain capacities of 3 to 5 percent, about 300 times that of conventional concrete).
- High fracture toughness.
- Autogenous healing of hairline cracks.
- Higher compressive strengths.

Applications

Because of its light weight, ECC has perhaps the greatest potential for use on bridges, bridge decks, and other highway structures.

Benefits

The benefits of ECC are similar to those offered by conventional FRC materials, such as improved structural integrity, resistance to plastic shrinkage, and improved post-cracking behavior. However, ECC goes beyond conventional FRC by also offering high tensile ductility and the potential for autogenous healing of hairline cracks.

Costs

No cost data are currently available regarding ECC. The unit cost of ECC is higher than conventional concrete, but because of its greater strength and ductility, reduced cross sections (and hence less material) may be required for a given application.

Current Status

ECC has seen use as a repair material for a bridge deck in Michigan, for a lightweight composite bridge deck in Japan, and as an infrastructure patching material in Japan and the United States. More widespread use and monitoring of in-service performance of ECC are needed to establish its viability.

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TITANIUM DIOXIDE–MODIFIED CONCRETE

Description

Titanium dioxide (TiO_2) is widely used as a white pigment in a number of products, such as paints, coatings, plastics, and toothpaste. In addition, TiO_2 is a potent photocatalyst that can break down almost any organic compound it touches when exposed to sunlight in the presence of water vapor (Frazer 2009). Recently, research has been conducted in adding TiO_2 to cement mortar to diminish the polluting effect of exhaust gases; in particular, nitrogen oxide is removed from the air and broken down into more environmentally benign substances that can be washed away by rainfall.

One product available that uses TiO_2 is TX Active® "smog-eating" cement manufactured by Italcementi over the last 10 years. A stretch of concrete pavement in Bergamo, Italy, was coated with a layer of TX Active, with claims of odor reductions within 4.5 mi^2 (11.7 km^2). This product was named one of the top 50 inventions of 2008 by *Time* magazine.

Applications

Although TiO_2-modified concrete could be used in almost any type of application, it may have greatest potential for use in urban areas where the levels of nitrogen oxides are greatest due to the higher volumes of traffic. In addition, the inclusion of TiO_2 helps maintain the whiteness of the cement, which may be important for certain aesthetic applications.

In addition to being used in conventional concrete, a thin layer of TiO_2 has been added to paver blocks used in urban street construction in Japan.

Benefits

As described above, the greatest benefit associated with the use of TiO_2 is the conversion of noxious nitrogen oxides into more environmentally friendly compounds.

Costs

No cost data are currently available, but costs for TiO_2 modified concrete are expected to be higher than for conventional concrete.

Current Status

There is considerable interest in the use of TiO_2 as a means of reducing nitrogen oxides, although some researchers believe that a more direct way of reducing nitrogen oxides (through improved automotive emission controls) may be more appropriate. Several cities, including London, are contemplating the use of TiO_2 in paving applications.

A test section that incorporates TiO_2 in the upper lift of a two-lift concrete pavement is under construction near Chesterfield, Missouri (as of October 2010). As part of the test section construction, Missouri DOT performed a detailed study of the concrete incorporating TiO_2.

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PERVIOUS CONCRETE

Description

Pervious concrete is a special type of concrete made of cementitious materials, water, admixtures, and narrowly graded coarse aggregate (Tennis, Leming, and Akers 2004). Containing very little or no fine aggregate and just enough cement paste to coat the aggregate, a system of interconnected voids (typically 15 to 35 percent) is created that provides a permeable concrete material capable of draining water very quickly (ACI 2006). Typical properties of pervious concrete include the following (Obla 2007):

- Slumps less than 0.75 in. (19 mm).
- In-place densities of 100 to 125 lb/ft^3 (1,602 to 2,002 kg/m^3).
- Compressive strengths from 500 to 4,000 lb/in^2 (3.4 to 27.6 MPa).

- Flexural strengths from 150 to 550 lb/in^2 (1 to 3.8 MPa).
- Permeability from 2 to 18 gal/min/ft^2 (81.5 to 733.4 L/min/m^2).

Applications

Pervious concrete has been used in a number of different applications, including parking areas, greenhouse floors, tennis courts, residential parking lanes, pedestrian walkways, pavements needing acoustic absorption characteristics, swimming pool decks, and low-volume roadways (ACI 2006). Pavement structures using pervious concrete are not intended to be subjected to heavy truck traffic. While pervious concrete has been successfully used throughout the warmer climates of the United States, there are some concerns about its use in areas subjected to severe freeze–thaw cycles. The National Ready Mixed Concrete Association has developed guidelines for using pervious concrete in areas prone to freeze–thaw conditions, focusing on such things as designing the pavement to limit the amount of saturation and incorporating a proper subbase course (NRMCA 2004).

Benefits

Pervious concrete offers a number of benefits, including the following (Chopra et al. 2007):

- Pervious concrete essentially serves as a retention pond, significantly reducing surface water runoff and reducing the need for curbing and storm sewers.
- Pervious concrete “filters” storm water that run through it, removing pollutants that would otherwise enter the groundwater, streams, or storage ponds.
- By allowing water to pass directly, pervious concrete helps recharge groundwater supplies.
- Pervious concrete helps improve road safety because of reduced hydroplaning potential.
- Pervious concrete can help absorb noise emissions.

Costs

The cost of pervious concrete can vary depending on the region, the type of application, and the size of the project, but some data suggest that pervious concrete can be 15 to 25 percent more expensive than conventional concrete.

Current Status

The use of pervious concrete has increased significantly in the last several years, perhaps largely because it is considered an environmentally friendly, sustainable product. The use of pervious concrete is among the “Best Management Practices” recommended by the U.S. Environmental Protection Agency and other agencies for the management of stormwater runoff on a regional and local basis. The inclusion of a pervious pavement is given additional LEED (Leadership in Energy and Environmental Design) credits, and a number of cities (including the City of Chicago in its “Green Alleys” initiative) and companies (including Wal-Mart) are incorporating pervious concrete into their construction programs.

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SELF-CONSOLIDATING CONCRETE

Description

Self-consolidating concrete (SCC) is a high-performance concrete that can flow easily into tight and constricted spaces without segregating and without requiring vibration (Szecsy and Mohler 2009). First used in the 1980s, the key to creating effective SCC is the development of a mixture that is not only fluid but also inherently stable so as to prevent segregation. Flowable properties are typically achieved with one or more of the following mix design attributes (Lange et al. 2008):

- High cementitious materials content (greater than 750 lb/yd^3 [445 kg/m^3]).
- Inclusion of next-generation superplasticizers (possibly in combination with a viscosity-modifying admixture).
- Inclusion of mineral admixtures (e.g., silica fume, fly ash, ground-granulated blast furnace slag), which help reduce the potential for segregation.
- Careful selection of aggregate volume and gradation. In particular, low aggregate volume and smaller coarse aggregate size are often needed to improve flow around steel reinforcement to reach restricted areas.

The flowability of SCC is measured in terms of spread when using a modified version of the slump test (ASTM C 143), and it typically ranges from 18 to 32 in. (457 to 813 mm) depending on the project requirements (NRMCA 2009).

Applications

SCC has been used in a variety of applications, including architectural concrete, columns, residential structures, beams, tanks, footers, and pumped concrete (NRMCA 2009). A recent construction project in Illinois used SCC for over 20 mi (32.2 km) of retaining wall structures along an interstate highway (Lange et al. 2008).

Benefits

There are a number of benefits associated with the use of SCC, including the following (NRMCA 2009):

- Faster placement rate with no mechanical vibration and less screeding, resulting in savings in placement costs.
- Improved and more uniform architectural surface finish with little to no remedial surface work.
- Ease of filling restricted sections and hard-to-reach areas.
- Improved consolidation around reinforcement and improved bond with reinforcement.
- Improved pumpability.
- Improved uniformity of in-place concrete by eliminating variable operator-related effort of consolidation.
- Shorter construction periods and resulting cost savings.
- Reduction or elimination of vibrator noise, potentially increasing available hours for construction in urban areas.

Costs

Although the material production costs for SCC are higher than for conventional concrete, overall cost savings can be realized with SCC because of increased productivity and reduced labor requirements.

Current Status

SCC continues to see increasing growth in usage in the construction industry, particularly in structural applications. Because of its unique properties, significant research has been performed to develop new test methods for characterizing SCC mixtures, such as the slump flow (ASTM C1611), the J-ring (ASTM C1621), and the column segregation (ASTM C1610) tests (Szecsy and Mohler 2009). Some research is also being conducted to identify suitable SCC mixtures for slip-form paving applications.

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SULFUR CONCRETE

Description

Sulfur concrete is made from sulfur collected from the petroleum refining process and coal ash from coal-burning power plants (FHWA 2005). The process applies vibration and pressure to a mixture of heated sulfur and coal ash, with the result being a dense, strong material that is highly resistant to acid and other chemicals. Sulfur concrete gains strength very rapidly, and can achieve compressive strengths in excess of 9,000 lb/in^2 (62.1 MPa) within 1 day (ACI 1993). The materials are impervious to moisture permeation and extremely resistant to attack by mineral acids and salts.

Applications

Sulfur concrete may be suitable for use in applications where conventional PCC may not be appropriate, such as saline environments or in areas exposed to chemicals or acids. Possible applications include industrial floors, bridge decks, tanks, pipes and pipe linings, and tunnel linings.

Benefits

The primary benefits of sulfur concrete are its rapid strength gain, dense matrix, and excellent durability and resistance to acids and chemicals. In addition, it has an environmental advantage, since it is produced using by-product and waste materials.

Costs

Cost data for sulfur concrete are not available.

Current Status

Although widely researched in the 1970s and early 1980s, sulfur concrete has not seen significant usage or research activity in the last decade. But given its high early strengths and resistance to chemicals and salts, there may be renewed interest in evaluating the suitability of sulfur concrete in transportation applications.

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AUTOCLAVED AERATED CONCRETE

Description

Autoclaved aerated concrete (AAC), sometimes referred to as autoclaved cellular concrete (ACC), is a lightweight precast structural product made from silica sand (AAC) or fly ash (ACC), gypsum, lime, cement, water, and an expansion agent (aluminum). It is an economical and sustainable construction block/panel material that provides thermal and acoustic insulation, as well as fire and termite resistance. While AAC is primarily manufactured for use in commercial, industrial, and residential buildings, it has potential application in the highways arena in the form of sound barrier walls for traffic noise mitigation.

AAC has been a popular building material in Europe for over 50 years and was first introduced in the United States about two decades ago. The manufacturing process involves grinding the sand (or fly ash) and gypsum to a consistency of powder and then mixing in the lime, cement, water, and aluminum (powder or paste form) (PCA 1991). After mixing, the slurry is poured into greased molds up to two-thirds of their depth (for load-bearing panels, rust-protected steel reinforcement mats are positioned into the molds prior to casting). The aluminum agent reacts with calcium hydroxide and water to produce hydrogen gas, which aerates the mixture (millions of microscopic, finely-dispersed cells) and causes it to expand by more than double in volume. The molds are placed in a pre-curing room for several hours, after which the semi-solid material is cut using steel wires to form the sizes required for the building elements. The material is then placed in an autoclave for 10 to 12 hours, whereby the steam pressure hardening process causes the sand to react with calcium hydroxide to form calcium silica hydrate, which increases its strength.

Depending on the application, the final AAC product is about 80 percent air by volume and has a density of approximately 45 lb/ft^3 (720.8 kg/m^3). The average minimum compressive strength of AAC ranges between 750 and 1,000 lb/in^2 (5.2 and 6.9 MPa). A typical noise reduction coefficient for unpainted AAC is 0.15, as compared to 0.02 for conventional concrete and 0.07 for concrete masonry. Also, the R-value for an AAC block 8 in. (203 mm) thick is about 13.28, as compared to 0.98 to 2.30 for a block of conventional concrete 8 in. (203 mm) thick (PCA 1991).

Manufactured panels are generally available in dimensions of 8 to 12 in. (203 to 305 mm) thick, 24 in. (610 mm) wide, and lengths up to 20 ft (6.1 m). Manufactured blocks are generally made 24, 32, and 48 in. (610, 813, and 1219 mm) long, between 4 and 16 in. (102 and 406 mm) thick, and 8 in. (203 mm) high. AAC can be cut or trimmed on-site with a handsaw to achieve the desired fit.

Construction of highway sound barrier walls using AAC typically consists of installing post (concrete or steel) and post foundations at specified intervals along the side of the road, and then setting and stacking the AAC panels into place between the posts to the specified height. Maintenance and repair are generally limited to individual panel replacements or cementitious patches to small damaged areas.

Applications

As previously described, in the highway arena AAC precast blocks and panels are generally most suitable for use as sound barrier walls along high-speed, high-volume highways located in noise-sensitive environments. In a similar application, they can be integrated with retaining walls and bridge parapets (Schnitzler 2006).

Benefits

AAC precast blocks/panels provide a highly effective, economical, and sustainable approach toward mitigating highway traffic noise. They possess excellent noise-dampening properties, are 100 percent recyclable, and, because they are lightweight and can be easily modified to size, can be installed quickly and efficiently.

Costs

The cost of AAC sound walls relative to other types of sound walls is highly variable and depends in large part on project location. Projects distantly located from the few places of manufacture will experience higher initial costs due to the additional transportation costs. On the other hand, the initial cost of precast AAC is reduced by the fact that the material can be installed more quickly than some other forms of sound walls.

Current Status

There are now only a few AAC/ACC manufacturing facilities in the United States. Although only a few States (e.g., Arizona, Georgia) have constructed significant amounts (estimated 100+ mi [161+ km]) of AAC sound barrier walls, it is expected that the beneficial properties of the material and the speed at which it can be installed will result in increased usage in the future.

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GEOPOLYMER CONCRETE

Description

The term geopolymer represents a broad range of materials characterized by chains or networks of inorganic molecules.[1] There are nine different classes of geopolymers, but those of greatest potential application for transportation infrastructure are composed of alumino-silicate materials that may be used to completely replace portland cement in concrete construction. These geopolymers rely on thermally activated natural materials (e.g., kaolinite clay) or industrial by-products (e.g., fly ash, slag) to provide a source of silicon (Si) and aluminum (Al), which are dissolved in an alkali-activating solution and then polymerize in chains or networks to create the hardened binder. Some of these systems have ancient roots, and have been used for

[1] http://www.geopolymer.org/science/introduction

decades, often being referred to as alkali-activated cements or inorganic polymer cements. Most geopolymer systems rely on minimally processed natural materials or industrial by-products to provide the binding agents, and thus require relatively little energy and release minimal amounts of CO_2 during production. Since portland cement is responsible for upward of 85 percent of the energy and 90 percent of the CO_2 attributed to a typical ready-mixed concrete, the energy and CO_2 savings through the use of a geopolymer can be significant.

The major drawback of current geopolymer technologies is their lack of versatility and cost-effectiveness compared to portland cement systems. Although numerous geopolymer systems have been proposed (most of which are patented), most suffer from being difficult to work with, requiring great care in production while posing a safety risk due the high alkalinity of the activating solution (most commonly sodium or potassium hydroxide). In addition, the polymerization reaction is very sensitive to temperature and usually requires that the geopolymer concrete be cured at elevated temperatures, effectively limiting its use to precast applications. Considerable research is underway to develop geopolymer systems that address these technical hurdles, creating a low-embodied energy, low-CO_2 binder that has properties similar to portland cement. In addition, research is also focusing on the development of user-friendly geopolymers that do not require the use of highly caustic activating solutions.

Applications

Currently, geopolymer concrete has very limited transportation infrastructure applications, being primarily restricted to international use in the precast industry. A blended portland-geopolymer cement known as Pyrament® (patented in 1984) has been used for rapid pavement repair, a technology still in use by the U.S. military along with geopolymer pavement coatings designed to resist the heat generated by vertical takeoff and landing aircraft.

Potential applications of geopolymers for bridges include precast structural elements and decks as well as structural retrofit using geopolymer fiber composites. To date, none of these potential applications is beyond the development stage.

Benefits

Benefits to be derived from the use of geopolymer concrete fit squarely into enhanced sustainability through increased longevity and reduced environmental impacts. The geopolymer systems under development for transportation infrastructure possess excellent mechanical properties and are highly durable, and therefore would result in increased longevity when used in harsh environments such as marine structures or pavements/structures exposed to heavy and frequent deicer applications. Furthermore, these systems rely on the use of industrial by-products (e.g., fly ash, slag). Most significantly, the widespread use of geopolymer concrete would significantly reduce the embodied energy and CO_2 associated with the construction of concrete transportation infrastructure, significantly reducing its environmental footprint.

Costs

The cost of geopolymer concrete is unknown, as it is still under development. The raw materials are not expensive and the equipment needed for geopolymer concrete is similar to that used to produce and handle conventional PCC. Systems need to be developed that are more user-friendly and less hazardous and that ideally can be used for cast-in-place applications at ambient temperatures. One concern is that many of the geopolymer systems that have been developed are patented, which will increase the cost of implementation.

Current Status

Research into geopolymer applications is at a fever pitch, from small startup companies to major international efforts. Australia and Europe have led significant past research efforts, but there has been a dramatic increase in research in the United States in recent years as interest in developing low-CO_2-emitting cementitious binders continues to grow. The first transportation application will likely be from the precast industry, but as of yet, there are no known producers of precast geopolymer concrete in the United States.

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HYDROPHOBIC CONCRETE

Description

Hydrophobic concrete is produced by introducing admixtures that shut down the active capillary transport mechanism and reduce absorption levels to less than 1 percent, as tested under the BSI 1881-122 procedure (CP 2006). While ordinary low water/cement ratio concrete absorbs from 3 to 5 percent, hydrophobic concrete absorbs less than 1 percent. Hydrophobic concrete has a long history of use in Australia, Asia, and Europe, and experience in the United States dates back to about 1999 (CP 2006).

Hycrete, Inc., of Carlstadt, New Jersey, markets a family of products that provide waterproofing and corrosion protection when added to concrete, thus rendering a hydrophobic material. These admixtures effectively seal internal capillaries that are responsible for water penetration into concrete, making the resultant product completely waterproof. As a result, for below-ground structures, external waterproof membranes, coatings, or sheeting treatments are no longer required, which increases productivity. The use of hydrophobic material also makes the concrete completely recyclable at the end of its life since it is the presence of those external waterproofing membranes that make concrete unsuitable for recycling. In addition, the product also provides corrosion protection by forming a protective coating around the steel reinforcement.

Applications

Primary applications for hydrophobic concrete include subgrade walls and slabs, elevated decks for parking structures, plazas and green-roof systems, tunnels, transportation infrastructure, and marine facilities (CP 2006). In the highway field, the most logical use of these hydrophobic concrete is in the construction of bridges, and several highway agencies have constructed experimental bridge projects featuring Hycrete admixtures (Wojakowski and Distlehorst 2009).

Benefits

As described in the preceding paragraphs, the primary benefits provided by hydrophobic concrete are the following (CP 2006; Wojakowski and Distlehorst 2009):

- The concrete is effectively waterproofed since the internal capillaries are sealed. This eliminates the need for any external waterproofing for below-ground structures, an activity that can be time- and weather-sensitive, so the overall construction schedule can be accelerated.
- The corrosion of embedded steel is prevented or reduced, not only by reducing the permeability of the concrete but also by forming a protective layer around the steel.
- A key environmental benefit is that concrete that would otherwise be waterproofed externally (through toxic chemicals and volatile organic compounds) can now be fully recycled at the end of its service life if it employed hydrophobic admixtures. In addition, concrete constructed with the Hycrete waterproofing admixtures has earned credit under the LEED program since savings in time and materials are realized.

Costs

Cost information on hydrophobic admixtures is not available. In applications where external waterproofing would otherwise be used, it is estimated that the use of hydrophobic concrete can save contractors between 20 and 60 percent (CP 2006).

Current Status

The use of hydrophobic concrete appears to be growing in the commercial structural industry, but in the highway arena only a few agencies have been experimenting with the technology, primarily in bridge applications. Among the agencies that have been evaluating this technology are the Connecticut, Kansas, New Jersey, and Ohio DOTs, and the U.S. Army Corps of Engineers (Wojakowski and Distlehorst 2009).

For More Information

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DUCTILE CONCRETE

Description

Ductal® is an ultra-high-strength, portland cement FRC premix that has been developed by the French cement manufacturing company Lafarge, in collaboration with two other French industrial groups, Bouygues and Rhodia. This material is designed to have high strength and high ductility, while also capable of being placed over a wide range of fluidities (from dry-cast to self-placing) depending upon the application. The manufacturer indicates that, in addition to the Ductal material's high strength and ductility characteristics, its microstructure makes it more resistant to freeze–thaw cycles, resistant to sulfates and various corrosive solutions, and resistant to abrasion and shocks (Lafarge 2010).

The components of the Ductal mix are cement, silica fume, mineral fillers (nano-fibers), water, fibers (metallic or organic), sand, and superplasticizer (Lafarge 2010). While the primary material is delivered as a dry premix, the metallic fibers (high carbon metallic) or organic fibers (polyvinyl alcohol), admixtures (superplasticizer), and water are added to the premix by the end user. Depending on the end-use application, the fibers typically make up 2 to 4 percent of the mix, whereas fibers typically make up 1 percent of the mix in more traditional fiber-reinforced mixes (Gerfen 2008).

Three different Ductal® products are available:

- Ductal®-FM: Ductal® premix with metallic fibers. Suitable for structural civil engineering applications such as load-bearing structures.
- Ductal®-AF: A variation of Ductal®-FM that includes the same mechanical properties and incorporates excellent standardized fire-resistance behavior.
- Ductal®-FO: Ductal® premix with organic fibers. Suitable for architectural applications such as wall panels, furniture, canopies, etc.

Strengths for the Ductal-FM premix are reported to be 23,000 to 33,000 lbf/in^2 (159 to 228 MPa) for compressive strength and 4,000 to 7,200 lbf/in^2 (28 to 50 MPa) flexural strength; while the Ductal-FO premix yielded slightly lower compressive strengths of 17,000 to 22,000 lbf/in^2 (117 to 152 MPA) and flexural strengths of 2,200 to 3,600 lbf/in^2 (15 to 25 MPa) (Klemens 2004).

Applications

Because the premix contains no large aggregate (i.e., the aggregate is in the sand-sized range), the combination of the fluidity of the material and the lack of need for traditional rebar reinforcement allows this material to be used in many different structural and nonstructural applications. While the material can be mixed in standard industrial type mixers, most applications to date have been precast concrete (Klemens 2004). Among the civil engineering and structural applications are structural beams, truss type structures, decks of steel bridges, slabs, panels, light poles, crash barriers, noise walls, pipes, blast protection, and vaults.

In 2006, the first North American Ductal® highway bridge was completed in Wapello County, Iowa, the result of 5 years of collaborative work between FHWA, Iowa DOT, Iowa State University, and Lafarge (CIF 2007). A simple, single-span bridge with a three-beam cross section utilized three 110-ft (33.5 m) Ductal girders with no rebar for shear stirrups. This project won a 2006 PCA Concrete Bridge Award.

Benefits

Because of its unique combination of strength, ductility, and durability, the manufacturer describes the following advantages of Ductal® over more traditional materials (Lafarge 2010):

- No need for conventional reinforcement.
- Great improvement of durability, with a resistance to permeability 50 times better than conventional high-strength concrete.
- Resistance to aggressive environments and loading from blasts.
- Permits the use of much thinner sections.
- Provides complete freedom on the shape of the section.
- Reduces the concrete volume of a structural member to only one third to one half of its conventional volume.
- Dramatically reduces the structural weight to be supported by a structure.
- Provides both direct and indirect cost savings.

Costs

While no reported material cost was found in any published resources, the manufacturer claims that the increased durability of the material does lead to reduced future maintenance costs.

Current Status

The Ductal material is available in the United States in several different formulations that are tailored to match the performance requirements of individual applications. Most of the experience to date has been in structural applications, with at least one highway bridge project constructed in the United States.

For More Information

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CHAPTER 4—CANDIDATE ASPHALT BINDER MATERIALS

SULFUR-EXTENDED ASPHALT

Description

Shell is marketing Shell Thiopave® to modify asphalt binder properties that would improve the performance of the extended AC mixtures. The Thiopave modifier consists of small pellets of sulfur modifier that are added to the asphalt mixture during the mixing process. The Thiopave melts rapidly on contact with the hot mix and is dispersed throughout the asphalt mixture during the mixing process

Applications

During the energy crisis period of the 1970s and early 1980s, the use of liquid sulfur as an extender of asphalt binder properties in hot-mix asphalt (HMA) was investigated. However, once the energy crisis was over, the interest in sulfur-extended asphalt binder subsided. In addition, during this period, sulfur-extended asphalt mixtures were produced using hot liquid sulfur that emitted a significant amount of fumes and odors unpleasant to workers. The transportation and supply of hot liquid sulfur were also problematic.

To replace the use of hot liquid sulfur for asphalt mixture production, solid sulfur pellets, known as Sulfur Extended Asphalt Modifier (SEAM) and recently renamed Shell Thiopave®, were further improved by Shell in the late 1990s. Thiopave is both a binder extender and an asphalt mixture modifier. The manufacturer reports that Thiopave can improve the performance of sulfur-extended asphalt mixtures, reduce construction costs and production temperatures, and provide more friendly conditions for sulfur-extended mixture production. Recent technological improvements in sulfur production, coupled with an increase in sulfur abundance, have led to resurgence in the exploration of the use of sulfur as an asphalt mixture modifier.

While the Thiopave pellets contain some additives designed to reduce odor and fumes during mixing, temperature control of the mixture and good ventilation practices are still required. Thiopave mixtures are typically produced at a target mixing temperature of 140 ± 5 ^{o}C (284 ± 41 ^{o}F). The mixtures must be produced above a temperature of 120 ^{o}C (248 ^{o}F) so that the sulfur pellets will melt and the sulfur will be dispersed throughout the asphalt mixture. Above mixing temperatures of 145 ^{o}C (293 ^{o}F), the potential for harmful emission generation greatly increases and could be problematic for workers involved in both the mixing and compaction processes.

The sulfur-extended asphalt can be used in warm-mix asphalt (WMA).

Benefits

According to Shell, Thiopave can significantly alter the performance properties of the mix. The change in these performance properties is dependent both on the percentage of virgin binder that is substituted with Thiopave and the amount of time the specimen is allowed to cure prior to performance testing. The most notable impact of the addition of Thiopave to an asphalt mixture is an increase in the stiffness of the mixture.

Literature has shown that the addition of Thiopave materials can have a positive impact on laboratory mixture performance. The addition of Thiopave has been shown to significantly increase the Marshall Stability and deformation resistance of asphalt mixtures in the laboratory after a 2-week curing period. The Thiopave material also had little negative impact in areas that were thought to be problematic, such as fatigue cracking resistance, low temperature cracking resistance, and moisture susceptibility.

Costs

No cost data are available. Costs are dependent on the global supply of sulfur and the state of the energy crisis.

Current Status of Usage

Thiopave-modified asphalt has been used in many countries and there are many pavement sections in Canada. In the United States, Shell has been involved in pavement sections in Los Angeles and Port of Oakland, the NCAT Pavement Test Track, and a section near Kansas City, Missouri. Shell will be involved the Louisiana Transportation Research Center/Louisiana DOT Accelerated Load Facility research project during 2010. Several other trials and projects are scheduled for 2010.

Resources/References

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BIO-DERIVED ASPHALT BINDERS

Description

Vegetable oil formulations (from soybean, corn, sunflower, and canola) are being investigated as possible modifiers for asphalt binders. Vegetable oil–based modifiers are considered renewable resources and are beginning to be used in other countries. These products include rejuvinators (extender oils), bio-polymers, and resin-like synthetic binders.

Applications

The bio-derived binders are considered applicable to a range of asphalt binders and uses.

Benefits

Similar to other asphalt binder modifiers and extenders, the vegetable oils improve specific properties of the asphalt binders and allow for partial replacement of the asphalt binders with the vegetable oils.

Costs

These materials have not been implemented in the United States, and no cost data are available.

Current Status of Usage

The bio-derived binders are commercially available in Europe and Australia, but have found little use in the United States.

Resources/References

King, Gayle, and King, Helen. *Asphalt Alternatives: Asphalt Contractor Options in a Market of Escalating Petroleum Prices and Dwindling Asphalt Supply*. Report No. SR-198, National Asphalt Pavement Association, Lanham, MD.

HIGH MODIFIED ASPHALT BINDERS

Description

High modified asphalt binders are asphalt cements that are blended with synthetic additives or chemical modifiers to enhance their physical properties for use in asphalt-aggregate mixes. The most common type of high modified asphalt binders are polymer-modified binders. Polymers are materials with long-chained molecular structures that, when mixed with asphalt cement (typically, at a rate between 3 and 6 percent by weight of the asphalt) and a chemical catalyst, dissolve and "cross link" with the asphalt to form a homogeneous binder material. Polymers include natural and synthetic rubbers (thermoplastic elastomers, such as styrene butadiene styrene [SBS] tri-block copolymer and styrene butadiene rubber [SBR] latex) and plastics (thermoplastic plastomers, such as ethyl vinyl acetate [EVA], ethylene glycidyl acrylate [EGA], and polyethylene).

Polymer-modified binders are seeing increasingly widespread use in HMA. The modified binder is more elastic and has improved low- and high-temperature stiffness (viscosity) properties that are better capable of meeting the performance requirements of the Superpave performance-graded (PG) asphalt binder specification (AASHTO M 320, AASHTO M 323), which are tied to the environmental and traffic conditions of the project site. Polymer-modified asphalt binders are typically specified and used in situations where the PG grade span (i.e., the low-temperature grade plus the high-temperature grade) is greater than 90 (e.g., PG 70−22). They exhibit the following binder-enhancement characteristics (WAPA 2002):

- Lower stiffness at the high temperatures associated with construction, thereby facilitating the pumping of the liquid asphalt binder as well as the mixing and compaction of the HMA in which the polymer-modified binder is used.
- Higher stiffness at high-service temperatures, resulting in reduced levels of rutting and shoving in the polymer-modified mix.
- Lower stiffness and faster relaxation properties at low service temperatures, resulting in reduced thermal cracking in the polymer-modified HMA.
- Increased adhesion between the asphalt binder and the aggregate in the presence of moisture, resulting in a reduced likelihood of stripping in the polymer-modified mix.
- Improved aging characteristics, which help delay the deleterious impacts of oxidation and provide a more durable pavement.

The construction and maintenance of pavements with polymer-modified HMA is similar to that of conventional HMA pavements. A number of highway agencies have constructed polymer-modified HMA pavements since their introduction in the late 1990s. Performance of these pavements has generally been good and has improved over the years corresponding to the advances in technology.

Applications

Polymer-modified asphalt binders are most commonly used in HMA mixes that are to be placed in high-stress applications. Typical locations include intersections with stop-and-go traffic, high-volume freeways and interstates, and high truck volume routes (D'Angelo n.d.). In addition, they are often used in areas of extreme climate (e.g., deserts or areas with very low temperatures).

Benefits

Although more expensive than neat asphalt binder, the use of polymer-modified binder in HMA can provide markedly improved performance in terms of reduced rutting, reduced fatigue cracking, and reduced thermal cracking, particularly in high-stress and climate-sensitive conditions. Depending on the costs and performance characteristics specific to a locale, the life-cycle costs of mixes that incorporate polymer-modified binders can be significantly lower than those of mixes using unmodified binders.

Costs

Bahia et al. (2001) estimated that the cost per ton of a modified binder is between 50 and 100 percent greater than that of neat asphalt cement, translating to an increase of 10 to 20 percent in the in-place cost of HMA. D'Angelo (n.d.) estimated that polymer-modification can increase the cost of virgin binder anywhere from 30 to 100 percent, which consequently increases the price of HMA by 10 to 40 percent.

Current Status

Polymer-modified asphalt binders have increasingly become the norm in designing optimally performing pavements, particularly in the United States, Canada, Europe, and Australia. Bahia et al. (2001) estimated that the use of modified asphalt binders in HMA was as much as 15 percent of the total annual tonnage of asphalt binder used in the United States. A later report by Tandon and Avelar (2002) indicated that 16 of 47 State agencies used modified binders. A 2005 survey by the Transportation Research Board (TRB) revealed that 34 States have established Superpave specifications covering modified binders.

For More Information

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CHAPTER 5—CANDIDATE ASPHALT CONCRETE MATERIALS

WARM-MIX ASPHALT CONCRETE

Description

WMA refers to technologies, originally developed in Europe, that are aimed at allowing the production and placement of HMA at lower temperatures. WMA is produced and mixed at temperatures roughly between 212 and 284 °F (100 and 140 °C), about 68–104 °F (38–58 °C) lower than an conventional HMA. This is achieved by using techniques that reduce the effective viscosity of the asphalt binder, allowing full coating of aggregates and subsequent field compaction at lower temperatures. The techniques to reduce the effective viscosity of the asphalt binder include:

- Organic additives, usually waxes or fatty amides.
- Chemical additives.
- Foaming techniques.

It should be noted that producing HMA at lower temperatures is the desired product to achieve the benefits, not the particular technology that is used to produce the WMA mix.

Applications

WMA is being used in all types of AC, including dense-graded, stone matrix asphalt, porous asphalt, and mastic asphalt. It is also being used in a range of layer thicknesses. WMA sections have also been constructed on roadways with a wide variety of traffic levels, from low to high.

WMA technology could have a significant impact on transportation construction projects in and around non-attainment areas such as large metropolitan areas that have air quality restrictions. The reduction in fuel usage to produce the mix would also have a significant impact on the cost of transportation construction projects.

The benefits of these technologies include worker safety, energy savings, air quality improvements, improved constructability, and longer performance due to reduced aging of the asphalt binder during the construction process. These technologies continue to be investigated.

Benefits

European countries are using WMA technologies to reduce energy consumption—burning fuels to heat traditional HMA to temperatures in excess of 300 °F (149 °C)—at the production plant. The lower production temperature of WMA results in the added benefit of reduced emissions from burning fuels, a cooler working environment for workers, and less fumes and odors generated at the plant and the paving site. Specific benefits related to the paving process include:

- Compaction—can be compacted at lower temperatures.
- Cold-weather paving—can extend paving season.
- Longer haul distances—extended time for hauling and compaction.
- Use of higher percentages of recycled asphalt pavement.
- Earlier opening to traffic.

Costs

The WMA cost is considered to be similar to the cost of conventional HMA.

Current Status of Usage

The European countries continue to increase the use of WMA. The consensus of the European countries using WMA is that WMA should provide equal or better performance than conventional HMA. Over 40 State highway agencies have constructed demonstration projects, and several agencies are using WMA on a regular production basis. The FHWA Office of Pavement Technology is actively involved with WMA technologies and is working in cooperation with FHWA Turner-Fairbank Highway Research Center's Bituminous Mixtures Laboratory to develop and monitor WMA demonstration projects and research and also to advance the knowledge and state of practice of these materials and technologies.

WMA is considered a viable technology and is beginning to be used in "production" paving in the United States. Because of the many advantages of WMA, its usage is growing in the United States and it is expected that the use of WMA will become standard practice. However, there are many elements of WMA that still need to be investigated.

Resources/References

European Asphalt Pavement Association. *The Use of Warm Mix Asphalt: EAPA Position Pa*per. June 2009.

National Center for Asphalt Technology has published the following reports, which are available at http://www.ncat.us/info-pubs/technical-reports.html:

- Report 06-02, "Evaluation of Evotherm for Use in Warm Mix Asphalt."
- Report 05-06, "Evaluation of Sasobit for Use in Warm Mix Asphalt."
- Report 05-04, "Evaluation of Aspha-Min Zeolite for Use in Warm Mix Asphalt."

National Cooperative Highway Research Program:

- Project 09-47, "Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies."
- Project 09-43, "Mix Design Practices for Warm Mix Asphalt Technologies."

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PERPETUAL ASPHALT PAVEMENT SYSTEMS

Description

A perpetual asphalt pavement system is defined as an HMA pavement that is designed and constructed to last for an extended time period (50 years or more) before requiring major structural rehabilitation or reconstruction. The system is designed such that the strain levels experienced at critical locations under traffic loadings are held below critical threshold values, thereby limiting the development of key structural distresses such as fatigue cracking and rutting. The perpetual asphalt pavement may only need periodic surface renewal (e.g., thin overlay, mill-and-fill) when surface distresses, such as transverse and longitudinal cracking or raveling, have reached unacceptable levels.

Perpetual asphalt pavements use multiple layers of durable asphalt mixtures, with each layer designed to accommodate the specific demands and constraints of the project (e.g., fatigue resistance, rutting resistance, safety, noise). The typical perpetual pavement cross section consists of the following layers (TRB 2001; Newcomb 2002):

1. A *surface course* (typically 1.5 to 3.0 in. [38 to 76 mm] thick) that consists of stone matrix asphalt, open-graded friction course, or Superpave dense-graded HMA designed to resist rutting and provide the friction, texture, and drainage characteristics needed for adequate safety and low noise generation.
2. An *intermediate/binder course* (typically 4 to 7 in. [102 to 178 mm] thick) that consists of a high-modulus Superpave dense-graded HMA designed to resist rutting and fatigue cracking via stone-on-stone contact and high-temperature graded binder.
3. A *base course* (typically 3 to 4 in. [76 to 102 mm] thick) that consists of flexible (low modulus) dense-graded HMA designed to resist fatigue cracking from bending under repeated traffic loads. Because the base course mix typically has a higher asphalt binder content to minimize moisture susceptibility problems, it is often referred to as a rich bottom base.

The concept of perpetual asphalt pavements is derived from the successful performance exhibited by many full-depth and deep-strength AC (FDAC and DSAC) pavements built by a number of highway agencies since at least the 1960s. The thick asphalt layers associated with these pavement structures provided good fatigue resistance, which often resulted in service lives that far exceeded the original 15- to 20-year lives for which they were designed (TRB 2001). Combined with the many advancements in asphalt mixture technology (e.g., modified binders, Superpave binder, and mix design) that have occurred over the years and the recent development of the Mechanistic-Empirical Pavement Design Guide (MEPDG), the FDAC and DSAC of old continue to evolve to meet the needs of modern highways.

The construction of a perpetual asphalt pavement depends on the specific design used. In some instances, the design may include a dense aggregate base on which the various asphalt layers will be placed (DSAC design). In others instances, the asphalt layers may be placed directly onto a prepared subgrade (FDAC design). Placement and compaction of the asphalt layers generally follow normal asphalt paving practices, with proper consideration given to the type of mix being placed.

Maintenance and rehabilitation of perpetual pavements is generally limited to preventive maintenance applications, such as crack sealing and traffic- and climate-appropriate surface treatments. Periodic resurfacing activities will be required, but such work is largely confined to the top portion of the pavement.

Applications

Perpetual asphalt pavements are generally most suitable for use on highways with moderate to high traffic volumes. They are not commonly used on lower volume roadways because of their significantly higher initial construction costs. Also, their use in urban environments where underground utilities are present is generally not recommended.

Benefits

Perpetual asphalt pavement systems provide a durable, safe, smooth, and long-lasting roadway without frequent expensive, time-consuming, traffic-disrupting reconstruction or major repair. Because of their long life with only periodic minor interventions, the system is also environmentally friendly.

Costs

The initial cost of a perpetual asphalt pavement may be anywhere from 10 to 25 percent more than a conventional HMA pavement, depending on the specific designs being compared. However, while the initial construction costs are higher, the overall life-cycle costs of a perpetual asphalt pavement are considerably lower when the extended pavement life and lower frequency of maintenance/rehabilitation activities are included.

Current Status

Perpetual asphalt pavements are being constructed by a number of State highway agencies, including those in Arkansas, California, Colorado, Delaware, Illinois, Kentucky, Michigan, Minnesota, Mississippi, Ohio, Oregon, Texas, Washington State, and Wisconsin. In addition, Canada and several European countries also have extensive experience with perpetual asphalt pavements.

For More Information

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POROUS ASPHALT PAVEMENT

Description

Porous asphalt pavements are specially designed pavements that use porous AC (PAC) mixes to laterally or vertically drain storm water runoff (Iowa LTAP 2007). PAC mixes have traditionally been used as surface courses on new asphalt pavement structures or as part of HMA overlays placed on existing pavements. Sometimes referred to as open-graded surface courses (OGSC) or porous/permeable friction courses (PFC), these surfaces are designed to facilitate storm water runoff and thereby prevent the development of water films that would otherwise decrease friction and increase splash/spray and hydroplaning potential. The high air void content inherent in the mix is also effective at absorbing tire-pavement noise emissions.

Recently, PAC mixes have been incorporated into full drainable pavement systems that substantially reduce runoff and promote natural infiltration of water into the soil. In this system, a somewhat thicker (2- to 4-in. [51- to 102-mm]) PAC layer is placed on top of a thin (1 to 2 in. [25 to 51 mm]) choke stone layer (typically 0.5-in. [13 mm] chips) and a thick (10 to 12 in.) aggregate recharge bed/reservoir course (with 1.5- to 2-in. [38- to 51-mm] stone), lined with a geotextile filter fabric. The PAC layer may consist of an OGSC/PFC layer and an asphalt-treated permeable base (ATPB) layer containing even higher voids. Storm water flows through the PAC surface into the aggregate recharge bed where it is stored and allowed to infiltrate into the soil between rainfalls (FPO 2008).

The PAC mixture consists of open-graded crushed aggregate (0.5- to 0.75-in. [13- to 19-mm] top size, with small amounts of sand or dust) and an asphalt binder (typically, 5.5 to 6.5 percent by weight of mix). In recent years, polymer-modified asphalt binders have been employed, which enable the use of higher air voids for better drainage (resulting in significantly less stripping in underlying asphalt layers) and higher binder content for improved adhesion between aggregate particles (resulting in less raveling) (APA 2002). In addition, fibers have been incorporated to control drain down of the asphalt binder from the aggregate during the construction process.

The system of interconnected voids inherent in PAC mixture design results in porosity levels between 10 and 20 percent and permeability levels anywhere between 350 to 6,000 ft/day (107 to 1,829 m/day). Such permeability levels are orders of magnitude higher than the best soil permeability of about 12 ft/day (3.7 m/day) and are capable of quickly draining high-intensity rainfalls (FPO 2008).

The placement of a PAC mix is essentially similar to that of a conventional HMA mix. A key exception is that the mix is only lightly compacted (two to three passes of a static steel-wheeled roller), so that the material retains its open nature for drainage.

The maintenance of PAC surface mixes is also similar to that of conventional HMA pavements, except that surface or fog seals are not recommended as they can block the internal drainage structure. Moreover, periodic cleaning is generally needed to remove contaminants that could plug the pavement and reduce its porosity. Finally, it is generally recommended that winter maintenance activities should exclude the use of abrasives or grits to prevent clogging; if the PAC structure is part of a parking lot intended to recharge groundwater, deicing chemicals should not be used (FPO 2008).

Applications

The use of PAC mixes for lateral surface drainage applications is fairly unrestricted. OGSC/PFC pavements have been and continue to be used on many types of pavement facilities, from high-volume freeways and major airport runways to lower-volume roads. They are generally not suitable for intersections or locations with heavy turning movements, nor for areas prone to heavy snowfall or subject to a lot of dirt or debris (Cooley et al. 2009).

The use of PAC mixes as part of full drainable pavement systems is currently limited, as it is a new design concept that is in the early stages of testing in the United States. Such testing is taking place primarily in urban settings on low-volume, light-traffic facilities like parking lots and subdivision roads.

Benefits

Benefits realized from the use of OGSC/PFC pavements are primarily associated with improved safety. They have been shown to improve wet weather frictional properties, reduce the potential for hydroplaning, reduce the amount of splash and spray, and improve visibility. Other benefits include resistance to permanent deformation, reduced tire–pavement noise levels, and smoother pavements (Cooley et al. 2009).

Benefits of full drainable pavement systems using PAC mixes include increased safety (due to a drained surface), potentially lower overall costs (due to the elimination or reduction in underground storm drainage systems), groundwater improvements (aquifer replenishment), and reduced environmental impact (due to reduced potential for flooding and erosion).

Costs

The cost of a PAC mix in relation to a conventional HMA mix varies widely. Mixes with minimal or no binder modifications are estimated to be between 5 and 25 percent higher in cost than conventional HMA, while those modified with polymers and fibers are estimated to be between 25 and 60 percent higher (FPO 2008; Root 2009).

Current Status

OGSC/PFC pavements are used by about 14 States, with only a few States (e.g., Texas, Georgia) using them on a significant number of projects. PAC full drainable pavements are being used for low-volume, light-traffic, large-expanse facilities, such as parking lots and local roads. These have seen limited use to date, but are generating considerable interest in light of the current sustainability movement.

For More Information

Flexible Pavements of Ohio (FPO). 2008. *Porous Asphalt Pavement*. Technical Bulletin. Flexible Pavements of Ohio, Dublin, OH. Online at http://www.flexiblepavements.org/documents/PorousTBSep08v1.pdf.

Iowa Local Technical Assistance Program (Iowa LTAP). 2007. "Popcorn Ball Pavement: Pervious Concrete and Porous Asphalt." *Technology News*, January-February 2007. Iowa State University, Ames, IA.

RECYCLED ASPHALT SHINGLES

Description

Recycled asphalt shingles (RAS) are waste roofing shingles salvaged for use in pavement construction materials (either as an aggregate supplement or in the modification of cold and hot asphalt mixes) as well as in other construction applications. The waste shingles are obtained from the demolition of existing roofs (referred to as "tear off" or "post consumer" shingles) or from factory rejects and tab cut-outs (referred to as "factory scrap" or "post industrial" shingles) resulting from shingle production (Griffiths and Krstulovich 2002).

To achieve the desired application size, both shingle types are ground and shredded in two to three stages using crushers, hammer mills, or rotary shredders. For HMA pavement applications (see AASHTO MP 15-09, *Standard Specification for Use of Reclaimed Asphalt Shingles as an Additive in Hot Mix Asphalt* and AASHTO PP 53-09, *Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in New Hot Mix Asphalt*), the desired size is typically less than or equal to 0.5 in. (13 mm); generally speaking, the smaller the shreds, the better they are incorporated into the mix (Vermont ANR 1999).

Roofing shingles are made of a supporting membrane of organic or fiberglass backing felt, a saturant of hot asphalt cement (for impregnating the felt), coatings of additional asphalt cement, and a coating of mineral fines (Griffiths and Krstulovich 2002). The compositional breakdown of asphalt shingles is as follows (Vermont ANR 1999):

- Fiberglass or cellulose backing: 5 to 15 percent.
- Asphalt cement saturant and coatings (from partial refinement of petroleum): 30 to 35 percent (organic shingles) or 15 to 20 percent (fiberglass shingles).
- Ceramic-coated, sand-sized, natural aggregate: 30 to 50 percent.
- Mineral filler/stabilizer (limestone, dolomite, silica): 10 to 20 percent (organic shingles) or 15 to 20 percent (fiberglass shingles).

The asphalt cement used for the saturant and coatings is harder than the asphalt binder used in HMA mixes. Thus, when it is combined with virgin asphalt binder, an increase in viscosity occurs.

The asphalt from post-consumer shingles is often in an irreversible, age-hardened state. Although this makes the grinding/shredding process easier as compared to post-industrial shingles, it can complicate the mix design of an RAS-modified HMA. Also, post-consumer shingles can potentially contain foreign materials (e.g., wood, nails) and asbestos, which can significantly add to the processing effort. Finally, as an additional consideration, post-consumer shingles usually contain a higher percentage of asphalt than post-industrial shingles because of the weathering loss of a portion of the ceramic-coated aggregate.

RAS-HMA formulation is based on two factors: climate and traffic (CMRA 2007). The target formulation is one in which the modified binder is stiff enough to resist pavement rutting in the summer months, yet soft enough to resist fatigue cracking due to repeated loading as well as cracking due to cold weather shrinkage of the pavement (Schroer 2009). Past research has indicated that RAS-HMA mixes with a maximum of 5 percent RAS (by weight of total mix) perform as well as conventional HMA mixes (CMRA 2007). However, higher percentages of RAS result in a significantly stiffer binder that is more susceptible to low-temperature cracking, although a softer virgin binder can counteract this effect. For example, recent research by the Missouri DOT indicates that when virgin asphalt comprises less than 70 percent of the total binder amount, a softer binder (PG 58-28 instead of PG 64-22) is needed to retain proper low-temperature viscosity (Schroer 2009).

The construction and maintenance of pavements with RAS-HMA is similar to that of pavements with conventional HMA. Several RAS-HMA test pavements have been constructed throughout the country, with short-term performance generally positive.

Applications

As mentioned earlier, highway pavement construction applications for RAS include aggregate supplement and modification of cold and hot asphalt mixes. In the most common application—RAS-HMA—the material can be used as a surface, intermediate, and/or base course for parking lots, lower-volume roads and highways, and paved shoulders for both highway and airport pavements. Testing for the acceptability of RAS-HMA on higher volume roads and highways and other airport pavement features is ongoing.

Benefits

In addition to the conservation of asphalt and aggregate materials and the overall reduction in solid waste, major benefits of RAS-HMA include a savings in the cost of the mix and reductions in (a) the amount of energy required to produce the mix and (b) the amount of greenhouse gas (CO_2) emissions associated with its production and placement (Robinette and Epps 2010).

Costs

The cost of RAS and RAS-HMA is dependent upon local market conditions. Because the price of asphalt binder and the price of processing asphalt shingles both fluctuate, the cost of RAS-HMA can also fluctuate. In general, however, the cost of processing the shingles tends to be offset by the savings in reduced amounts of virgin asphalt binder and fine aggregate. The cost of RAS-HMA is slightly to considerably less than the cost of conventional HMA (2 to 15 percent for mixes with RAS content less than or equal to 5 percent) (Robinette and Epps 2010).

Current Status

Several States have experimented with the use of RAS-HMA, including Florida, Georgia, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nevada, New Jersey, New York, North Carolina, Pennsylvania, Tennessee, and Texas (Vermont ANR 1999; Griffiths and Krstulovich 2002). Currently, 14 highway agencies have Standard Specifications or Special Provisions that allow up to 5 percent post-industrial and/or post-consumer shingles in HMA (Robinette and Epps 2010).

For More Information

Construction Materials Recycling Association (CMRA). 2007. *Recycling Tear-Off Asphalt Shingles: Best Practices Guide*. Construction Materials Recycling Association, Eola, IL. Online at http://www.shinglerecycling.org/sites/www.shinglerecycling.org/files/shingle_PDF/ShingleRecycling-BPG-DFK-3-22-2010.pdf.

Griffiths, C. T., and J. M. Krstulovich. 2002. *Utilization of Recycled Materials in Illinois Highway Construction*. Report No. IL-PRR-142. Illinois Department of Transportation, Springfield, IL.

Robinette, C., and J. Epps. 2010. “Energy, Emissions, Material Conservation and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement.” Paper prepared for the 89th Annual Meeting of the Transportation Research Board, Washington, DC.

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Vermont Agency of Natural Resources (Vermont ANR). 1999. *Recycled Asphalt Shingles in Road Applications: An Overview of the State of the Practice*. Online at www.anr.state.vt.us/dec/wastediv/recycling/shingles.pdf.

CHAPTER 6—CANDIDATE METALLIC AND POLYMER MATERIALS

VITREOUS CERAMIC COATINGS FOR REINFORCING STEEL

Description

Most concrete pavements include steel as part of their design and construction, whether it is for reinforcement in the slabs (e.g., deformed longitudinal bars used in CRCPs), load transfer across transverse joints (e.g., smooth dowel bars in jointed plain concrete pavements), or connectors across longitudinal joints (e.g., tie bars across adjacent pavement lanes). Generally, such steel in concrete is protected from corrosion by a passive oxide film that forms in the high pH environment; however, if this film is disrupted or penetrated by caustic chloride ions, corrosion of the steel can occur, the products of which create a severe volume change that can lead to cracking, spalling, or delamination of the concrete.

To address these concerns, most highway agencies are using epoxy-coated dowel bars and tie bars, and some agencies are using epoxy-coated reinforcing steel for CRCP. This adds an additional layer of protection to the steel from the ingress of chloride ions. However, the epoxy coating may become damaged or may still be susceptible to corrosion under some conditions, and therefore may not provide the desired long-term performance. Furthermore, in the case of CRCP, there are concerns about the suitability of the bond between the epoxy-coated steel and the concrete.

In an effort to reduce corrosion, some agencies are evaluating the use of non-corrodible materials or non-corrodible coatings that are expected to provide a higher degree of protection than conventional epoxy coating. Vitreous ceramic coatings are an example of materials being evaluated as alternatives to epoxy coatings. These coatings not only reduce the corrosion potential but also promote better bonding between the steel and the concrete (when such bonding is desired). This material is a specially formulated durable glass that is fused to metal under very high temperatures (typically 1,100 to 1,600 ^{o}F [593 to 871 ^{o}C]). This process forms a layer at the interface that merges the chemical makeup of the glass and the underlying metal, the result of which are very high bond strengths (10,000 to 12,000 lb/in^2 [703 to 842 kg/cm^2]) between steel and enamel (Weiss et al. 2009).

Vitreous enamel coatings typically have hardness levels in the range of 3.5 to 6 on the Mohs hardness scale, whereas organic coatings are in the range of 2 to 3. These coatings generally are resistant to fracture and to moisture penetration (Weiss et al. 2009).

Applications

The applications for vitreous ceramic coatings include the following:

- Dowel bars for jointed concrete pavements.
- Tie bars for jointed concrete pavements.
- Longitudinal reinforcing steel for CRCP.

Benefits

The use of vitreous ceramic coatings is expected to provide the following benefits:

- Reduced corrosion, which potentially increases the life of the concrete pavement. This is becoming more critical as more and more highway agencies are designing for concrete pavements with 40 to 60 year lives. The inclusion of effectively sized, corrosion-resistant, dowel bars is imperative to fully achieve those longer design lives.
- Increased concrete–steel bonding (where needed), which provides improved performance of CRCP. In CRCP designs, effective bonding between the continuous, longitudinal reinforcing steel and the concrete is critical to the development of an acceptable crack spacing pattern for long-term performance. Furthermore, the increased bonding may lead to potentially improved constructability of CRCP designs by reducing splice lengths of the longitudinal reinforcing.

Costs

No cost data are currently available for this product. Costs are expected to be higher than for conventional epoxy-coated steel reinforcing.

Current Status

Laboratory testing of this product has been completed that demonstrated the increased bonding levels and the reduced potential for corrosion.

For More Information

Weiss, C. A., S. W. Morefield, P. G. Malone, and M. L. Koenigstein. 2009. "Use of Vitreous-Ceramic Coatings on Reinforcing Steel for Pavements." *Proceedings, National Conference on Preservation, Repair, and Rehabilitation of Concrete Pavements*. Federal Highway Administration, Washington, DC.

FIBER-REINFORCED POLYMER BARS FOR CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

Description

CRCP is a long-lasting, premium pavement often used in urban corridors subjected to heavy truck traffic. Containing no regularly spaced transverse joints, a key feature of CRCP design is the use of deformed longitudinal steel reinforcing bars that are designed to create tight, hairline cracks at intervals of approximately 3 to 8 ft (0.91 to 2.44 m). However, corrosion of the steel reinforcement has compromised the performance of CRCP designs in some areas, and in response a number of agencies have adopted the use of epoxy-coated reinforcing steel to minimize the problem. Nevertheless, this coating can be damaged during construction, once again leading to corrosion problems, and the epoxy coating reduces the bond between the concrete and the steel, which can affect the steel design requirements and also increase the lap length required on splices of the bars.

Due to these concerns, alternative materials that are more corrosion-resistant are being considered for the longitudinal reinforcement in CRCP designs and one material in particular that has seen some application is FRP bars. FRP composite materials consist of a matrix of polymeric material (polyester, vinyl ester, or epoxy) that is reinforced by fibers or other reinforcing materials (fiberglass, carbon fibers, or graphite fibers) (FHWA 2009). Filler materials (such as calcium carbonate, clay, or hydrated alumina) may also be added to improve specific properties of the composite or to lower its costs.

Applications

The applications for FRP bars in CRCP include:

- Longitudinal reinforcement.
- Transverse reinforcement on chairs to support longitudinal bars.
- Transverse tie bars between adjacent lanes or ramps.

Benefits

The use of FRP bars in CRCP projects is expected to provide the following benefits (FHWA 2009):

- Reduced corrosion, thereby potentially increasing the life of the concrete pavement. This is becoming more critical as more and more highway agencies are designing concrete pavements with 40- to 60-year lives.
- Lighter weight of bars, which makes them easier to handle during placement.

In addition, the electromagnetic transparency of FRP bars makes them suitable for use at toll collection booths where electromagnetic vehicle detectors are used (FHWA 2009).

Costs

No current cost data are available for the use of FRP bars in CRCP. The cost of FRP reinforcing bars is higher than conventional epoxy-coated steel bars, and higher reinforcement contents are required when using FRP bars in CRCP. Consequently, the use of FRP in CRCP is expected to be more expensive than using epoxy-coated, steel deformed reinforcing bars.

Current Status

Two experimental field projects have been constructed recently in North America. One was constructed in Quebec in 2006 and contained 18 different experimental sections including three sections with galvanized steel reinforcement (Thebeau, Eisa, and Benmokrane 2008). A second project was constructed in West Virginia in 2007, featuring one FRP-reinforced CRCP section and one black-steel-reinforced control section (Chen et al. 2008). Performance evaluations of these experimental sections are underway.

For More Information

Chen, R. H. L., J.-H. Choi, H. V. GangaRao, and P. A. Kopac. 2008. “Steel Versus GFRP Rebars?” *Public Roads*, Vol. 72, No. 2. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2009. *Evaluating the Use of FRP Bars in Continuously Reinforced Concrete Pavements*. FHWA-HIF-09-012. FHWA, Washington, DC.

Thebeau, D., M. Eisa, and B. Benmokrane. 2008. “Use of Glass FRP Reinforcing Bars instead of Steel Bars in CRCP in Quebec.” *Proceedings CD*, *9th International Conference on Concrete Pavements*, San Francisco, California.

FIBER-REINFORCED POLYMER DOWEL BARS

Description

Dowel bars have been shown to be very effective in preventing transverse joint faulting and ensuring a long-lasting, smooth-riding surface for jointed concrete pavements. Traditionally, smooth, round, solid steel bars have been used, with an epoxy coating for protection against corrosion. However, with many agencies moving toward longer life concrete pavements (40 to 60 years) and because of concerns about the long-term effectiveness of epoxy coatings, there is increased interest in investigating the use of alternative dowel bars that have improved corrosion resistance (FHWA 2009).

One product that shows promise as a replacement for steel dowel bar is FRP bar. FRP composite materials consist of a matrix of polymeric material (polyester, vinyl ester, or epoxy) that is reinforced by fibers or other reinforcing materials (fiberglass, carbon fibers, or graphite fibers) (FHWA 2009). Filler materials (such as calcium carbonate, clay, or hydrated alumina) may also be added to improve specific properties of the composite or to lower its costs. Although FRP material is widely used in the United States as reinforcing bars in structural applications, there has not been much use of FRP bars as a load transfer device in concrete pavement joints. During the last 20 years, several demonstration projects have investigated the use of alternate dowel bar materials, and many of these projects included FRP dowel bars (HITEC 2005; Porter et al. 2005, 2006; Eddie, Shalaby, and Rizkilla 2001). The findings from these studies indicate mixed performance for joints incorporating FRP bars. A recent study sponsored by FHWA found that FRP dowels were good alternatives to traditional steel dowels for transferring joint loads in concrete pavements (Vijay et al. 2009).

Applications

FRP bars can provide positive load transfer in jointed concrete pavements. During the summer of 2010, Idaho DOT elected to use about 36,000 FRP dowel bars for a 10-lane-mile new concrete pavement project along a section of I-84. Also, the use of FRP dowel bars has been approved by Virginia DOT, and agencies in other States (Wisconsin, New Jersey) have plans to construct test sections that incorporate FRP dowel bars.

Benefits

The use of FRP bars for load transfer at concrete pavement joints is expected to provide the following benefits:

- Reduced corrosion, thereby potentially increasing the life of the concrete pavement. This is becoming more critical as more and more highway agencies are designing concrete pavements with 40- to 60-year lives.
- Lighter weight of bars, which makes them easier to handle during placement.
- In addition, electromagnetic transparency, which makes FRP bars suitable for use at toll collection booths where electromagnetic vehicle detectors are used.

Costs

No current cost data are available for the use of FRP dowel bars in larger construction projects. Based on the use of the dowel bars in the Idaho project, it appears that use of FRP dowel bars is cost-competitive with the conventionally used epoxy-coated steel bars.

Current Status

Idaho DOT is installing about 36,000 FRP dowel bars along a section of I-84. New Jersey DOT is testing the use of FRP bars in precast concrete repair applications. Virginia DOT has approved the use of FRP bars in new concrete pavement construction.

For More Information

Eddie, D., A. Shalaby, and S. Rizkilla. 2001. Glass Fiber-Reinforced Polymer Dowel for Concrete Pavements," *ACI Structural Journal*, March–April.

HITEC. March 2005. "Evaluation of Alternative Dowel Bar Materials," report prepared by Applied Pavement Technology, Inc., Highway Innovative Technology Evaluation Center, Washington, DC.

Porter, M. L., et al. June 2005. *Field Evaluation of Elliptical Fiber Reinforced Polymer Dowel Performance*, Report No. DTFH61-01-X-00042, Project 5, FHWA, Washington, DC. www.intrans.iastate.edu/reports/frp_dowel.pdf

Porter, M. L., et al. April 2006. *Laboratory Study of Structural Behavior of Alternative Dowel Bars*, Report No. DTFH61-01-X-00042, Project 7, FHWA, Washington, DC. http://publications.iowa.gov/4407/.

Vijay, P. V., V. S. GangaRao Hota, and H Li. September 2009. *Design and Evaluation of Jointed Plain Concrete Pavement with Fiber Reinforced Polymer Dowels*, Report No. FHWA-HRT-06-106. Federal Highway Administration, Washington, DC.

ZINC-CLAD DOWEL BARS

Description

Dowel bars have been shown to be very effective in preventing transverse joint faulting and ensuring a long-lasting, smooth-riding surface. Traditionally, smooth, round, solid steel bars have been used, with an epoxy coating for protection against corrosion. However, with many agencies moving toward longer life concrete pavements (40 to 60 years), and because of concerns about the long-term effectiveness of epoxy coatings, there is increased interest in investigating the use of alternative dowel bars that have improved corrosion resistance (FHWA 2009).

One relatively new material that is seeing some use on a limited basis is rolled zinc alloy–clad dowels. In this application, zinc cladding of 0.040-in. (1.02 mm) minimum thickness is placed over a Grade 60 carbon steel bar. These dowels have exhibited superior corrosion resistance during laboratory studies (Snyder 2005) and have seen some limited use in long-life pavements in Minnesota, Pennsylvania, and Ohio (Miller 2006).

Applications

Zinc-clad dowel bars provide positive load transfer in jointed concrete pavements, and are allowed as an alternative dowel bar in at least three States (Minnesota, Washington, and Michigan).

Benefits

The primary benefit of zinc-clad dowel bars is their superior resistance to corrosion (as compared to conventional, epoxy-coated bars) at only a slightly higher cost. They are also expected to be less susceptible to damage during transportation and construction operations.

Costs

The cost of zinc-clad dowel bars is slightly higher than conventional epoxy-coated dowels (by a factor of about 1.6) but less than stainless steel and FRP alternatives.

Current Status

Currently, zinc-clad dowel bars are being allowed as an acceptable alternative material by at least three highway agencies. A number of laboratory studies comparing them with other alternative materials have been completed or are underway. While laboratory experiments have been promising, long-term performance data are not available.

For More Information

Federal Highway Administration (FHWA). In press. *Alternative Dowel Bars for Jointed Concrete Pavements*. ACPT TechBrief. FHWA, Washington, DC.

Miller, W. 2006. *Cathodically Protected Load Transfer Dowels for High-Performance Pavements*. www.allzinc.com/techdata/Lifejacket_Dowel06.pdf. Accessed September 2, 2009.

Snyder, M. B. 2005. “An Evaluation of Cathodically Protected Dowels for Concrete Pavements,” in *Proceedings of the Eighth International Conference on Concrete Pavements*, Colorado Springs, CO, 2005.

MICROCOMPOSITE STEEL FOR DOWELS AND TIE BARS

Description

As described above, the quest for alternative dowel bars with high corrosion resistance has become a critical issue as agencies move towards the construction of long-life concrete pavements. Microcomposite steel (a proprietary product of the MMFX Technologies Corporation, sometimes simply referred to as MMFX steel) is a relatively new material that contains less than 1 percent carbon and typically 8 to 10 percent chromium, making it more corrosion resistant than carbon steel (FHWA 2009). The MMFX 2 smooth round dowel bar is available in 1.25- and 1.5-in. (32- and 38-mm) diameters.

Applications

MMFX bars provide positive load transfer in jointed concrete pavements, and currently are allowed as an alternative in at least two States (Minnesota and Washington). This material can also be manufactured in a deformed configuration for use as a tie bar across lanes.

Benefits

Laboratory studies have shown microcomposite steel to be superior in corrosion resistance to conventional carbon steel and similar to epoxy-coated steel, although several laboratory studies comparing it to other metallic materials have shown mixed results (Clemeña 2003; Mancio et al. 2008). The cost of MMFX bars is also only slightly higher than conventional epoxy-coated steel bars, making them attractive as a potential alternative dowel bar material.

Costs

Recent data suggests that MMFX is about 1.4 times the cost of conventional epoxy-coated steel bars, and less expensive than zinc-clad, FRP, or stainless steel bars.

Current Status

MMFX steel bars have seen a limited amount of use in field studies, but they are being specified for use by the Washington State DOT in certain environments (FHWA 2009). Wisconsin has completed a 5-year field evaluation indicating generally good performance, but not necessarily superior to that being provided by epoxy-coated bars (Battaglia 2008). Laboratory evaluations of this material have been completed or are underway to compare performance with other metallic options including stainless steel and epoxy-coated steel. Long-term field performance data are not available.

For More Information

Battaglia, I. K. 2008. *Evaluation of MMFX 2 Steel Corrosion-Resistant Dowel Bars in Jointed Plain Concrete Pavement*. Report No. WI-03-08. Wisconsin Department of Transportation, Madison, WI.

Federal Highway Administration (FHWA). In press. *Alternative Dowel Bars for Jointed Concrete Pavements*. ACPT TechBrief. Federal Highway Administration, Washington, DC.

Clemeña, G. G. 2003. *Report on the Investigation of the Resistance of Several New Metallic Reinforcing Bars to Chloride-Induced Corrosion in Concrete*. Report No. VTRC 04-R7. Virginia Transportation Research Council, Richmond, VA.

Mancio, M., C. Carlos, Jr., J. Zhang, J. T. Harvey, and P. J. M. Monteiro. 2007. *Laboratory Evaluation of Corrosion Resistance of Steel Dowels in Concrete Pavement*. Final Report UCPRC-RR-2005-10 (FHWA No. S/CA/RI-2006/27). California Department of Transportation, Sacramento, CA.

CHAPTER 7—AGGREGATE MATERIALS

SYNTHETIC AGGREGATES

Description

Synthetic aggregates are manufactured using industrial waste material or by-products. These materials may be used as replacement for aggregates in AC or PCC.

Applications

There are three groups of synthetic aggregates.

1. Group 1 is created from waste product that is heated in a blast furnace or rotary kiln to temperatures between 1,000 and 1,500 ^{o}F (538 and 816 ^{o}C), and then turned into pellets. Waste materials generally used in this process include sewage sludge, incinerated sewage sludge, pulverized fuel ash, oil sands, slag and other solid waste materials. High amounts of natural gas and electricity are needed to fuel the kilns and furnaces to eliminate bacteria and produce the pellets. The pellets/extrusions are cooled, sized, crushed, and graded to meet the job specification. Smokestack pollution can be a by-product. The cost for this group is comparable to production of mineral-based expanded shales and clays. The strength ranges from low to medium, except for the slag pellets, which fall in the high range. The synthetics in this group weigh about the same as standard mineral aggregate. The limitations can be the size of the pellets. Slag aggregate cannot be used where the irons may leach from the concrete when water is present, or in esthetic uses where slag would stain or leach from the concrete.

2. Group 2 combines only non-cementitious fly ash with a binder, which is then pressed or extruded into pellets. In Group 2, the pellets/extrusions are cooled, sized, crushed, and graded to meet a job specification. The cost of this production can vary with the supply of ash and energy, and their primary market is road-base and lightweight concrete. This technology uses less energy than Group 1 blast furnace or kiln processes. The pellet size limits the size of the aggregate.

3. Group 3 combines recycled products such as non-cementitious fly ash, bottom ash, mine tailings, recycled plastics, recycled glass and other recycled materials. This group's primary market is lightweight concrete where high compressive and tensile strength is of primary concern, such as in skyscrapers, bridges, buildings, cultured stone, and roofing materials. It uses both fly ash varieties (non-cementitious and cementitious) and bottom ash (the major waste products from coal plants), and it can be mixed by formula to include plastics or other recyclable materials. The combined materials are pressed or extruded into a solid block. The solid block is then crushed with a standard rock crusher into a lightweight aggregate. All standard aggregate sizes are available. The aggregates are high-strength, lightweight—with weights ranging from 10 to 50 lb/ft^3 (160 to 801 kg/m^3), and can be used in multiple industries. The ultra-lightweight concrete weighs 95 lb/ft^3 (1,522 kg/m^3), with compressive strength of 6,000 lbf/in^2 (41.4 MPa), and a tensile strength of 11 percent of the compressive strength.

The synthetic aggregate products can be produced and stockpiled during the construction off-season for use during the next construction season.

Benefits

The primary benefit of synthetic aggregates is that industrial waste products are productively used. These products can also serve as replacement for more expensive aggregates or local aggregates of marginal quality.

Costs

Costs are reported to be comparable to natural aggregates. Many of the processes for producing synthetic aggregates are patented, and costs may vary by the process used.

Current Status

Synthetic aggregates are widely used in nonhighway applications and also for light-weight concrete for transportation structures. However, there has been very little application of synthetic aggregates, except for slag aggregates, in pavement construction.

For More Information

Western Research Institute: The Synag Process for producing ash-based pelletized lightweight aggregates. http://www.netl.doe.gov/technologies/coalpower/ewr/coal_utilization_byproducts/utilization/wri.html.

David Shulman. 2005. "Synthetic Aggregates—A Look at the Three Groupings of Synthetic Aggregates and the Potential Uses for Each," *Pit & Quarry Magazine*, August 1.

MANUFACTURED AGGREGATES USING CAPTURED CO_2

Description

A process—The Calera Process—is under development by Calera Corporation to manufacture calcium and magnesium carbonate using mineralized CO_2 captured from power plant flue gas to create aggregates that can be used to produce concrete.

Applications

The manufactured aggregates can be used as partial or total replacement of natural aggregates used in paving and structural concrete.

Benefits

Two important benefits are expected from this process. The first is the availability of good quality aggregates at locations where sound aggregates may be in short supply. The second is the sequestering of CO_2 produced by coal-powered plants.

Costs

Costs estimates are not available as full-scale production has not started.

Current Status

A pilot manufacturing plant to produce calcium and magnesium carbonate aggregate is under development (as of early 2009).

For More Information

Cecily Ryan, Terence Holland. 2009. “Next Generation Paving Materials Using Mineralized CO_2 Captured from Flue Gas,” abstract submitted for the International Conference on Sustainable Concrete Pavement Technologies, held in Sacramento, California, September 2010, organized by the Federal Highway Administration.

Engineering News-Record, February 18, 2009, “New Green-Concrete Process Combines Seawater, Flue Gas.”

MATERIALS THAT ALLOW INTERNAL CONCRETE CURING

Description

Internal curing is the process by which the hydration of cement occurs because of the availability of additional internal water that is not part of the original mixing water. This additional water is typically supplied by using relatively small amounts of saturated, lightweight, fine aggregates (LWAs) or by the addition of super-absorbent polymers (SAPs) in the concrete (Bentz, Lura, and Roberts 2005). Once the original mixing water is used up, additional water is drawn from the LWA or SAP to promote more complete hydration of the cementitious materials. The amount of additional water available is dependent on both the volume and the absorption capacity of the aggregate (Cleary and Delatte 2008).

Internal curing is especially beneficial in low water-to-cementitious material ratio (w/cm) concrete (say, below ~0.42) because of the increased potential for autogenous shrinkage, defined by the American Concrete Institute (20l0) as the “change in volume produced by continued hydration of cement, exclusive of effects of applied load and change in either thermal condition or moisture content” (p. 79). With more agencies moving towards lower w/cm concrete (for strength and durability reasons), there is an increased potential for early-age cracking to occur, particularly if inadequate curing methods are used during construction (Lam 2005). Furthermore, internal curing may be more necessary with concretes that use supplementary cementitious materials (fly ash, slag cement, or silica fume), another common feature of today’s highway concrete mixtures.

When LWA is used to provide internal curing, a portion of the fine aggregate is replaced with the LWA. The amount of LWA that should be used is a function of type, size, degree of moisture pre-conditioning of the LWA, and type and amount of binder (Cleary and Delatte 2008). Some initial guidance is available on determining the amount of partial replacement of the fine aggregate in a concrete mixture with LWA (Bentz, Lura, and Roberts 2005).

Applications

The applications for internal curing concrete include most transportation facilities, including bridges, parking structures, highway and street pavements, parking lots, and overlays.

Benefits

There are a number of purported benefits associated with internal curing, including the following (Bentz, Lura, and Roberts 2005; Cleary and Delatte 2008):

- Reduced early-age shrinkage, particularly in concretes with low w/cm.
- Increased concrete strength (compressive, flexural, and tensile strength).
- Reduced permeability.
- Increased durability.

Costs

No cost data are currently available for this concrete produced using either LWA or SAP.

Current Status

A number of laboratory studies have been conducted evaluating concrete produced using either LWA or SAP (Lam 2005; Cleary and Delatte 2008). These laboratory studies have demonstrated the effectiveness of internal curing in promoting more complete cement hydration. At the same time, LWA has been used in the construction of bridge decks and in residential paving in North Texas for several years (Villarreal and Crocker 2007). A number of agencies continue to evaluate the merit and potential benefits that could be reaped from internal-curing concrete.

For More Information

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Bentz, D. P., P. Lura, and J. W. Roberts. 2005. “Mixture Proportioning for Internal Curing.” *Concrete International*, Vol. 27, No. 2. American Concrete Institute, Farmington Hills, MI.

Cleary, J., and N. Delatte. 2008. “Implementation of Internal Curing in Transportation Concrete.” *Transportation Research Record: Journal of the Transportation Research Board 2070*. Transportation Research Board, Washington, DC.

Lam, H. 2005. *Effects of Internal Curing Methods on Restrained Shrinkage and Permeability. PCA R&D Serial No. 2620*. Portland Cement Association, Skokie, IL.

Villareal, V. H., and D. A. Crocker. 2007. “Better Pavements through Internal Hydration.” *Concrete International*, Vol. 29, No. 2. American Concrete Institute, Farmington Hills, MI.

CHAPTER 8—OTHER MATERIALS

ULTRA-THIN BONDED WEARING COURSE

Description

Also referred to as an ultra-thin friction course, an ultra-thin bonded wearing course consists of a thin (0.375- to 0.75-in. [9.5 to 19 mm] thick) gap-graded, polymer-modified HMA layer placed on a polymer-modified emulsified asphalt membrane. This material was originally developed in France in 1986 and introduced in the United States in the early 1990s as the proprietary product NovaChip®.

An ultra-thin bonded wearing course is typically applied as a preventive maintenance or minor rehabilitation treatment for the purpose of sealing the surface, correcting surface distresses (e.g., raveling, block cracking), or restoring key surface characteristics, such as friction, smoothness, and transverse profile. The polymer-modified HMA layer uses crushed aggregate chips sized 0.25 to 0.5-in. (6.4 to 12.7 mm) with binder contents in the range of 4.5 to 5.5 percent.

Similar to HMA, an ultra-thin bonded wearing course is easily produced at a HMA facility and placed with little difficulty (Kandhal and Lockett 1997). The main difference in placement is the use of a specialized paver, which is capable of applying the asphalt membrane and the polymer-modified HMA surfacing in a single pass. Once placed, the material is lightly rolled to orient and seat the aggregate chips.

Recent research on the performance of ultra-thin bonded wearing course indicates life expectancies between 7 and 12 years when placed on HMA-surfaced pavements and 5 to 10 years when placed on concrete-surfaced pavements (Peshkin et al. 2009). A study on the performance of ultra-thin bonded wearing courses placed on concrete surfaces in North Carolina suggested services lives of 6 to 10 years (Corley-Lay and Mastin 2007).

Applications

Ultra-thin bonded wearing course is most suitable for use on existing HMA-surfaced pavements that are in structurally good condition (Peshkin et al. 2009). While it can also be used with success on concrete pavements, its performance on concrete pavements is often compromised because of joint reflection cracking issues. Ultra-thin bonded wearing course can be used on a variety of pavement facilities, ranging from parking lots and low-volume roads to high-volume rural and urban highways.

Benefits

In addition to preserving existing pavements via sealing and correction of surface distresses, ultra-thin bonded wearing courses provide benefits in the areas of user safety (improved friction, reduced splash/spray, and reduced hydroplaning potential) and comfort (increased smoothness and reduced noise). In addition, unlike certain surface treatments, ultra-thin bonded wearing courses do not experience aggregate chip loss due to their excellent adhesion properties.

Costs

Although the cost of ultra-thin bonded wearing course depends largely on the location, specific application, and size of the project, typical construction costs may range from about \$4.00/yd^2 to \$6.00/yd^2 (\$4.78/m^2 to \$7.18/m^2) (Peshkin et al. 2009).

Current Status

The use of ultra-thin bonded wearing course in the United States is fairly significant. In 2001, upwards of 6.6 million yd^2 (5.5 million m^2) of NovaChip® were reportedly placed, with key users being Alabama, Arkansas, Illinois, Maryland, Michigan, Ohio, and Pennsylvania (Russell et al. 2008). Since then, a number of other highway agencies (including Minnesota, Washington, Texas, California, and New Mexico) have used ultra-thin bonded wearing courses in a number of applications with generally good success. A project in Minnesota shows excellent performance after 7 years of service (Ruranika and Geib 2007).

For More Information

Corley-Lay, J., and J. N. Mastin. 2007. “Ultrathin Bonded Wearing Course as a Pavement Preservation Treatment for Jointed Concrete Pavements.” Paper presented at the 2007 Annual Meeting of the Transportation Research Board, Washington, DC.

Kandhal, P. S., and L. Lockett. 1997. *Construction and Performance of Ultrathin Asphalt Friction Course*. NCAT Report No. 97-5. National Center for Asphalt Technology, Auburn, AL.

Peshkin, D., K. L. Smith, A. Wolters, J. Krstulovich, J. Moulthrop, and C. Alverado. 2009. *Guidelines for the Preservation of High Traffic Volume Roadways*. Draft Final Report, Strategic Highway Research Program 2 Project R-26. Strategic Highway Research Program, Washington, DC.

Ruranika, M. M., and J. Geib. 2007. *Performance of Ultra-Thin Bounded Wearing Course (UTBWC) Surface Treatment on US-169, Princeton, MN*. MN/RC-2007-18. Minnesota Department of Transportation, Maplewood, MN.

Russell, M. A., L. M. Pierce, J. S. Uhlmeyer, and K. W. Anderson. 2008. *NovaChip®*. Report No. WA-RD 697.1. Washington State Department of Transportation, Olympia, WA.

ADVANCED CURING MATERIAL

Description

The SINAK Corporation recently developed a lithium-based curing compound called Lithium Cure™, which is a water-based lithium compound with a proprietary formula in solution that contains no volatile organic compounds or solvents and requires no mixing or agitation (SINAK 2009). The compound can be placed earlier than conventional curing materials and, when applied to freshly placed concrete prior to initial set, the accompanying lithium reaction produces additional gel that significantly reduces moisture loss, thereby producing a more efficient hydration process and eliminating surface restraint cracking (SINAK 2009).

Applications

SINAK Lithium Cure™ can be used on virtually any type of concrete material, including roadway pavements, bridges, pre-cast elements, and cast-in-place elements (SINAK 2009). The material is purportedly particularly effective for slip-form pavements, in which it can be applied directly behind the paving equipment in a single coat. If a separate texturing machine is used, Lithium Cure is applied immediately after the final texturing. Typical application rates vary, but typically range between 300 and 400 ft^2 per gallon (7.4 to 9.8 m^2/L) for slip-form paving, between 500 and 700 ft^2 per gallon (12.3 to 17.2 m^2/L) for pre-cast concrete, and between 400 to 500 ft^2 per gallon (9.8 to 12.3 m^2/L) for cast-in-place concrete (SINAK 2009).

Benefits

According to the manufacturer, Lithium Cure provides the following benefits (SINAK 2009):

- Can be applied earlier than conventional curing compounds (immediately after the paver or texturing machine).
- Eliminates surface restraint cracks (micro-cracking).
- Retains high internal moisture content.
- Reduces permeability.
- Increases long-term durability.
- Produces additional cement gel.
- Promotes more efficient hydration process.

The benefits of Lithium Cure are expected to be most evident in hot, windy, low-humidity environments. The application of Lithium Cure does not interfere with the bonding of joint sealants, patching or surface coating materials, paints, or lane markers (SINAK 2009).

Costs

Cost data are currently not available.

Current Status

Lithium Cure is a relatively new product and has not yet seen widespread use. It has been applied on a new concrete pavement construction project on the North-South Road in Honolulu, Hawaii (Gomaco 2009).

For More Information

Gomaco World (Gomaco). 2009. "A Big Project on a Small Island." *Gomaco World*, Vol. 37, No. 2. Gomaco Corporation, Ida Grove, IA.

SINAK Corporation (SINAK). 2009. *Product Information Sheet—Lithium Cure™*. SINAK Corporation, San Diego, CA.

WORKABILITY-RETAINING ADMIXTURE

Description

The BASF Construction Chemical Company recently developed a new concrete admixture formulated to retain slump and control workability without retardation. The product, RheoTEC™ Z-60, provides more consistent concrete that helps producers achieve more cost-effective and efficient operations, even under changing materials and environmental conditions (CM 2009). In essence, the admixture is dosed to provide workability retention for a desired length of time, with improvements in both early and later-age strength development while minimally affecting set. RheoTEC meets the requirements of ASTM C 494/C494M, *Standard Specification for Chemical Admixtures for Concrete—Type S, Specific Performance Admixtures*.

Applications

RheoTEC™ Z-60 is recommended for use in virtually all types of concrete, including ready-mixed concrete, precast concrete, and SCC mixtures. It may be particularly effective in concrete with varying slump requirements, concrete mixtures that employ supplementary cementitious materials, and concrete where high flowability, increased stability, and improved durability are required (BASF 2009). The recommended dosage range for RheoTEC is between 3 and 12 fl oz (88.7 to 355 mL) per cwt of cementitious materials.

Benefits

According to the manufacturer, RheoTEC Z-60 provides the following benefits (BASF 2009):

- Promotes greater consistency of concrete workability at the job site.
- Promotes consistency in compressive strengths via minimized job site addition of water.
- Minimizes re-dosing of high-range water-reducing admixtures at the job site.
- Provides consistent air contents.
- Allows for an expanded concrete delivery range.
- Provides quicker truck turnaround times.
- Results in fewer rejected loads and better customer satisfaction due to consistent quality of concrete.

RheoTEC Z-60 will neither initiate nor promote corrosion of steel reinforcement embedded in the concrete.

Costs

Cost data are currently not available.

Current Status

RheoTEC Z-60 was introduced in mid-2009 and is being promoted to concrete producers and consumers. No information is immediately available regarding its use in actual construction projects.

For More Information

BASF Construction Chemicals (BASF). 2009. *Product Data Sheet—RheoTEC Z-60*. BASF Construction Chemicals, Cleveland, OH.

Concrete Monthly (CM). 2009. “New BASF Admixture Retains Workability Without Retardation.” *Concrete Monthly*, August 2009 Issue. Publications and Communications, Inc., Austin, TX.

CONCRETE SURFACE SEALERS

Description

Concrete surface sealers effectively reduce or prevent the ingress of moisture, chloride ions, sulfate ions, and other substances that may contribute to damaging reactions in the concrete (Sutter et al. 2008). Concrete surface sealers may be divided into a number of different families, with one such grouping as follows (Cady 1994):

- Water repellants, which penetrate concrete pores to some degree and coat pore walls rendering them hydrophobic (e.g., silanes, siloxanes).
- Pore blockers, which have sufficiently low viscosity to penetrate and seal the pores in concrete while leaving little or no measurable coating on the surface of the concrete (e.g., resins, linseed oil).
- Barrier coatings, which are too viscous to penetrate pores to measurable depths but form surfacing coatings of significant thickness and block the pores (e.g., epoxies, urethanes, and acrylics).

Satisfactory performance of the concrete is still strongly dependent on the development of durable mix designs and effective construction, and surface sealers may be considered in areas where significant deicing chemicals are applied or where concrete durability is suspect. For concrete bridge elements, it is recommended that for the use of sealers to be economical, the chloride ion content at the depth of the shallowest 1 percent of the reinforcing steel should be less than 1 lb/yd^3 (0.59 kg/m^3) and the corrosion potential (half-cell) should be more positive than -250 mV (Cady 1994).

Although all surface sealers can slow the penetration of deicing chemicals, one study showed that siloxane sealants were particularly effective at slowing the ingress of deicing chemicals into concrete or mortar; silane sealants were also effective, but to a lesser extent (Sutter et al. 2008). The FHWA’s ASR program notes that the application of silane (or siloxane) compounds has been effective in reducing the rate of ASR development in field applications (FHWA 2008).

Applications

Surface sealers may be applied to any horizontal concrete structure exposed to deicing chemicals or other adverse contaminants, but may be most appropriate where very high concentrations of such contaminants are expected, such as bridge decks, parking lots, and perhaps intersections, or on concrete whose durability is suspect. The effectiveness of surface sealers is lost after they are exposed to traffic and environmental forces, and they may need to be reapplied after 3 to 5 years.

Benefits

The primary benefit provided by surface sealers is to reduce the ingress of deleterious substances that would contribute to degradation of the concrete and reduced service life.

Costs

Costs for surface sealers are highly variable depending on the type of material and the application rate, but can range from about \$0.10 to \$0.70 per ft^2 (\$1.08/m^2 to \$7.53/m^2).

Current Status

A number of highway agencies are evaluating concrete surface sealers, particularly for use on their bridge decks. Generally speaking, silanes and siloxanes have exhibited the best performance. Wisconsin, Minnesota, Florida, and Illinois are among the highway agencies with active research in this area.

For More Information

Cady, P. D. 1994. *Sealers for Portland Cement Concrete Highway Facilities*. NCHRP Synthesis of Highway Practice 209. Transportation Research Board, Washington, DC.

Federal Highway Administration (FHWA). 2008. “Got ASR? Mitigation Options for Concrete Structures Affected by ASR.” *Reactive Solutions–An FHWA Alkali-Silica Reactivity News Publication*, Vol. 1, No. 3. FHWA, Washington, DC. Available at http://www.fhwa.dot.gov/pavement/concrete/reactive/issue04.pdf.

Sutter, L. L., K. Peterson, G. Julio-Betancourt, D. Hooton, T. Van Dam, and K. Smith. 2008. *The Deleterious Chemical Effects of Concentrated Deicing Solutions on Portland Cement Concrete*. Final Report SD2002-01F. South Dakota Department of Transportation, Pierre, SD.

CHAPTER 9—SUMMARY

As indicated at the beginning of this report, every year large amounts of aggregate materials and manufactured materials are used to support highway construction and rehabilitation in the United States. However, the poor availability of good quality aggregates in many parts of the country and the increasing financial and societal costs to produce the needed manufactured materials are creating a concern for the planners and engineers. It is, therefore, important that new and improved sources of highway construction materials be developed that will result in improved performance of the highway system, be cost effective, and incorporate sustainable technologies.

This white paper reviewed the availability of advanced construction materials for highway application to improve or replace conventionally used construction materials. These advanced construction materials can be categorized as follows:

- New/Innovative materials to replace currently used materials.
- New/Innovative materials that are less expensive.
- New/Innovative materials that result in longer service life.
- New/Innovative materials that result in sustainable solutions.
- New/Innovative materials that improve the properties of marginal materials.
- Waste and recycled materials that are optimized for use.

The criteria for inclusion of specific advanced construction materials in this white paper include the following:

- The selected materials have been recently introduced (less than 5 years in the marketplace) and not widely used.
- The selected materials are under development.

The characteristics of the advanced construction materials discussed in this report are summarized in Table 1. As indicated in this report, these materials encompass a broad range of developmental stages. The materials range from materials under development to recently commercialized materials. The commercialized materials have typically not been widely implemented and their performance histories have not been established yet.

It is hoped that this report will help establish the potential for considering the use of alternative materials discussed in this report or encourage agencies and industry to accelerate the development and implementation of products still under development.

It is recommended that FHWA review the information presented in this report with stakeholder groups to help prioritize the product development and implementation that meet States' needs and that can be supported at the national level.

TABLE 1—ADVANCED CONSTRUCTION MATERIALS

Advanced Materials	Replace Conventional Materials	Less Expensive	Longer Life	Sustainable Solutions	Improve Properties	Recycled Materials	Status
Cementitious Materials							
Performance-specified cements	Yes	Yes		Yes	Yes	Yes	Available
Next-generation sustainable cements	Yes	NA	Yes	Yes	Yes	Yes	Under development
Eco-friendly cements	Yes	NA		Yes	Yes	Yes	Under development
Energetically modified cement	Yes	Yes		Yes	Yes	Yes	Available
Concrete Materials							
Engineered cement composites	Yes	NA	Yes	NA	Yes	NA	Available
Titanium dioxide–modified concrete	No	No	No	Yes	No	No	Available
Pervious concrete	Yes	No	NA	Yes	Yes	NA	Available
Self-consolidating concrete	Yes	NA	NA	NA	Yes	NA	Available
Sulfur concrete	Yes	NA	NA	Yes	NA	NA	Available
Autoclaved aerated concrete	Yes	NA	NA	NA	Yes	NA	Available
Geopolymer concrete	Yes	NA	Yes	Yes	Yes	NA	Under development
Hydrophobic concrete	Yes	NA	Yes	NA	Yes	NA	Available
Ductile concrete	Yes	No	Yes	NA	Yes	NA	Available

NA = information not available

TABLE 1—ADVANCED CONSTRUCTION MATERIALS (continued)

Advanced Materials	Replace Conventional Materials	Less Expensive	Longer Life	Sustainable Solutions	Improve Properties	Recycled Materials	Status
Asphalt Binder Materials							
Sulfur-extended asphalt	Yes	NA	Yes	Yes	Yes	NA	Available
Bio-derived asphalt binders	Yes	NA	NA	Yes	Yes	NA	Under development
High modified asphalt binders	Yes	Yes	Yes	NA	Yes	NA	Available
Asphalt Concrete Materials							
Warm asphalt mixtures	Yes	No	Yes	Yes	Yes	No	Available
Perpetual asphalt pavements	Yes	Yes	Yes	Yes	Yes	No	Available
Porous asphalt pavement	Yes	No	Yes	Yes	Yes	No	Available
Recycled asphalt shingles	Yes	Yes	NA	Yes	Yes	Yes	Available
Metallic and Polymer Materials							
Vitreous ceramic coatings for reinforcing steel	Yes	No	Yes	NA	Yes	No	Under development
Fiber-reinforced polymer bars for continuously reinforced concrete pavements	Yes	Yes	NA	NA	Possibly	No	Available
Fiber-reinforced polymer dowel bars	Yes	Yes	NA	NA	Possibly	No	Available
Zinc-clad dowel bars	Yes	No	Yes	NA	Yes	No	Available
Microcomposite steel for dowels and tie bars	Yes	No	Yes	NA	Yes	No	Available

NA = information not available

TABLE 1—ADVANCED CONSTRUCTION MATERIALS (continued)

Advanced Materials	Replace Conventional Materials	Less Expensive	Longer Life	Sustainable Solutions	Improve Properties	Recycled Materials	Status
Aggregate Materials							
Synthetic aggregates	Yes	NA	Yes	Yes	Yes	Yes	Available
Manufactured aggregates using captured CO_2	Yes	NA	Yes	Yes	Yes	NA	Under development
Materials that allow internal concrete curing	No	Yes	Yes	Yes	Yes	NA	Available
Other Materials							
Ultra-thin bonded wearing course	Yes	Yes	Yes	NA	Yes	NA	Available
Advanced curing material	Yes	No	NA	NA	Yes	NA	Available
Workability-retaining admixture	No	No	Yes	NA	Yes	NA	Available
Concrete surface sealers	No	NA	Yes	NA	Yes	NA	Available

NA = information not available