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TWO-LIFT CONCRETE PAVING FOR SUSTAINABLE PAVEMENTS

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ABSTRACT

Two-lift concrete pavement, sometimes referred to as composite pavement, is an innovative technique that involves placing a thinner portland concrete layer over a thicker portland concrete layer at a specified interval. A shortage of suitable aggregates for use in concrete pavements in some regions of the world has become a very serious concern for some organizations. Importing aggregates from faraway locations is neither economical nor practical/sustainable; therefore, the use of local materials is highly desirable. The strength of two-lift concrete pavement technology lies in being able to utilize any of the following for the bottom lift: locally available aggregates, manufactured sands, high-coefficient of thermal expansion (CoTE) aggregates, recycled concrete aggregates (RCA), fractionated reclaimed asphalt pavements (FRAP), lower cement content, or a higher amount of supplementary cementitious materials (SCMs). Some of these materials, however, may not be allowed to be used in single-lift concrete pavements due to issues related to polishing, durability, or strength gain. This paper gives a thorough overview of the historical background, potential environmental and sustainable advantages, and practical challenges related to two-lift pavement.

Keywords: Two-lift concrete pavement; Sustainability; Manufactured and recycled aggregates; Reclaimed asphalt pavement; Supplementary cementitious materials; Cost Analysis

INTRODUCTION

Two-lift concrete pavement, sometimes referred to as composite pavement, is an innovative technique that involves placing a thinner portland concrete layer with high quality aggregates over a thicker portland concrete layer made with locally available aggregates within 30 to 90 minutes to ensure adequate bonding. The top lift typically has a thickness ranging from 40 to 80 mm and contains good quality aggregate to enhance polishing and skid resistance, noise reduction, and durability. The lower lift, in contrast, is designed to provide adequate structural performance, with a thickness varying from 180 to 260 mm, depending on the expected traffic loading and the properties of the subgrade and base. The strength of the technology lies in the fact that the bottom lift can be constructed using locally available aggregates, manufactured sands, high CoTE aggregates, RCA, FRAP, lower cement content, and a higher amount of supplementary cementitious materials (SCMs).

Some of these materials may not be allowed in single-lift concrete pavements due to polishing, durability, or early strength gain issues. However, the use of such materials in the bottom lift can reasonably be justified for the following reasons: First, the bottom lift is not directly exposed to traffic loading and the same environmental conditions as the top lift; and second, the bottom layer is normally protected by a high-quality layer in the top lift, which eliminates the risk of surface polishing, excessive thermal gradient, or unsatisfactory ride quality and noise concerns. Nevertheless, additional costs and logistics are associated with two-lift concrete pavements, including using two spreaders, slip-form pavers, concrete batch plants, additional labor and crew, and more complex timing and coordination. These potential challenges and concerns can, if not addressed, impede the practical application of two-lift concrete pavement. The overall functional and structural performance, as well as the construction requirements with regard to fresh concrete properties, strength gain, curing, and surface texturing for two-lift pavement are the same as for single-lift pavement.

The use of two-lift concrete pavement in the United States is rarely used compared to conventional concrete pavements. The primary purpose of this paper is to discuss the historical background, U.S. and European experiences with two-lift pavement, and the potential environmental and sustainable benefits of and practical challenges posed by two-lift pavement. This paper is intended to promote the use of two-lift concrete paving for sustainable pavements.

HISTORICAL BACKGROUND

The two-lift pavement technique is not a new concept and has been around for more than a century. The first concrete pavement in the United States was constructed as a two-layer pavement system in Bellefontaine, Ohio, in 1891 (Snell and Snell, 2002). The city constructed 6100 square meters of two-lift concrete pavement with top and bottom thicknesses of 50 and 100 mm, respectively, around the public square between 1893 and 1894 (Portland Cement Association, 1915). The bottom layer had a water-to-cement ratio of 0.6 and contained larger aggregates (38 mm), whereas the top layer contained a water-to-cement ratio of 0.45 with durable aggregates (38 mm). The Bellefontaine two-lift pavement was overall still in a good condition after 15 years of service, despite some construction issues, which resulted in worn longitudinal joints (Iowa State College, 1919).

The number of concrete pavements significantly increased between 1900 and 1914 (Moorefield and Voshell, 1915), and an innovative paving system called granitoid concrete pavement was patented in Chicago, Illinois, in 1907. In addition, several granitoid concrete pavement projects were constructed with this technology across the U.S. from 1907 to 1925 (Hoffbeck, 1990; Iowa State College, 1919). Figure 1 shows the embedded bronze plates in pavements constructed by the R. S. Blome Company. In 1906, the R. S. Blome Company constructed granitoid concrete blocked pavement for the village of Red Jacket, Michigan, currently known as the village of Calumet (Mailloux et al., 2008), and in 1911 it did so for the city of Grand Fork, North Dakota (Hoffbeck, 1990), whereas the Texas Granitoid Company did the same for Belknap Place in San Antonio (Taubert, 2014). Some parts of these pavements are still in service. Figures 2 through 6 present the original and current state of these granitoid concrete pavements.

Figure 1. Embedded bronze plates in pavements constructed in San Antonio, TX (Taubert and Prusinski, 2014**),** and in the village of Calumet, MI (Mailloux et al., 2008).

The granitoid concrete paving standards at that time were intended to provide long-term structural and durability performance through proper pavement design, material selection, and good construction practices (Hoffbeck, 1990; Mailloux et al., 2007; Taubert, 2014). With respect to the structural design, the top and bottom thicknesses were typically 50 and 125 mm, respectively, to sustain traffic loading (carriages) and environmental conditions. Additionally, the standards required that the street bed (subgrade) be 150 mm of unbound gravel and sand to prevent frost heaving. With regard to material selection and mixture design, the 125-mm bottom lift concrete consisted of 1 part portland cement, 4 parts of crushed stone, and 3 parts sand, manually mixed on a mixing board. Water was also gradually added until a stiffer concrete was achieved. Unlike the bottom lift, the 50-mm top mixture design consisted of 1 part of portland cement and 1 ½ parts durable and fine-grained granite sand. As for the manner of construction, the construction practices required that the subgrade be appropriately arched to provide better drainage and that the granitoid concrete pavement be laid in 1.5-m sections and sealed with asphalt and rubber to accommodate thermal expansion and contraction, which is currently known as jointed pavement. Moreover, the top surface was then brushed to prevent slipperiness and scored with 100 by 220 mm blocks to give better footing for horses.

A two-lift concrete pavement system in the sense of placing a portland concrete layer over another portland concrete layer was commonly constructed in the United States between 1950 and the mid-1970s, due to its suitability and practicality (Cable et al., 2004). The standard paving construction practice involved first placing the bottom-lift concrete up to mid-depth , then laying down the wire mesh reinforcement while the concrete was still in its plastic condition, and finally covering the bottom and wire mesh reinforcement with the top-lift concrete (Cable et al., 2004). It is evident that the concrete mixture design and material selection for the top and bottom lifts were the same as for single-lift concrete pavements.

The two-lift concrete pavement technique became very rare from the mid-1970s to 2000 because the concrete paving industry switched to jointed concrete pavement design, as well as to a narrower paving width of 6 m, as opposed to 30 m for the two-lift concrete system (Cable et al., 2004). However, a few experimental two-lift concrete pavement sections developed by High Performance Concrete Pavement (HPCP) were constructed in the 1990s in Michigan and Kansas. These experimental concrete pavement sections were considered the initial research to evaluate the two-lift concrete pavement system in terms of design, materials, and construction (Tompkins et al., 2009).

The two-lift concrete pavement system has also been used in European countries, including Germany, France, the Netherlands, and Switzerland, since the 1930s (Darter, 1992; Hall et al., 2007; Smith et al., 1998). In recent decades, the use of local aggregates, reclaimed paving materials, recycled aggregates, exposed-aggregate concrete, and good friction and noise characteristics in two-lift concrete pavements have always been more prevalent in Europe than in the United States, as indicated in Table 1. In fact, the standard construction practice for concrete pavements in Austria is two-lift paving (Hall et al., 2007; Smith et al., 1998). In the United States, several federal concrete pavement initiatives have been launched in the last two decades to identify the techniques adopted in the European two-lift concrete pavements with regard to materials, design, construction, and maintenance, so that they can be implemented in the U.S. to achieve longer service lives. Tompkins et al. (2009) listed the following federal initiatives:

1. The U.S. Tour of European Concrete Highways, initiated in 1992 (Darter, 1992);
2. The High Performance Concrete Pavement (HPCP) Test and Evaluation Project 30, also initiated in 1992 (Wojakowski, 1998);
3. The International Technology Scanning Program tour of long-life concrete pavements in Europe and Canada, initiated in 2006 (Hall et al., 2007); and
4. The Transportation Research Board’s second Strategic Highway Research Program (SHRP2) R21 Composite Pavements Project.

A few two-lift concrete pavement projects have been constructed in the United States over the last decade in areas where the bottom lift used local aggregates, manufactured sands, recycled concrete, reclaimed asphalt pavements, or high-CoTE aggregates; these took place in Kansas, Minnesota, Illinois, and Texas. These two-lift concrete pavement projects aimed at prompting contractors, engineers, aggregate manufacturers, and highway agencies to consider this paving technology in areas where local aggregates, recycled materials, lower-volume cement, higher quantities of SCMs, or high-CoTE aggregate in the lower lift. This approach provides potential economic, environmental, sustainable, durable, and structural benefits that can outweigh its possible challenges. Table 1 presents the European and U.S. experiences with two-lift concrete pavements.

Figure 2. Original and current extents of granitoid pavement in Calumet, MI (Mailloux et al., 2008)

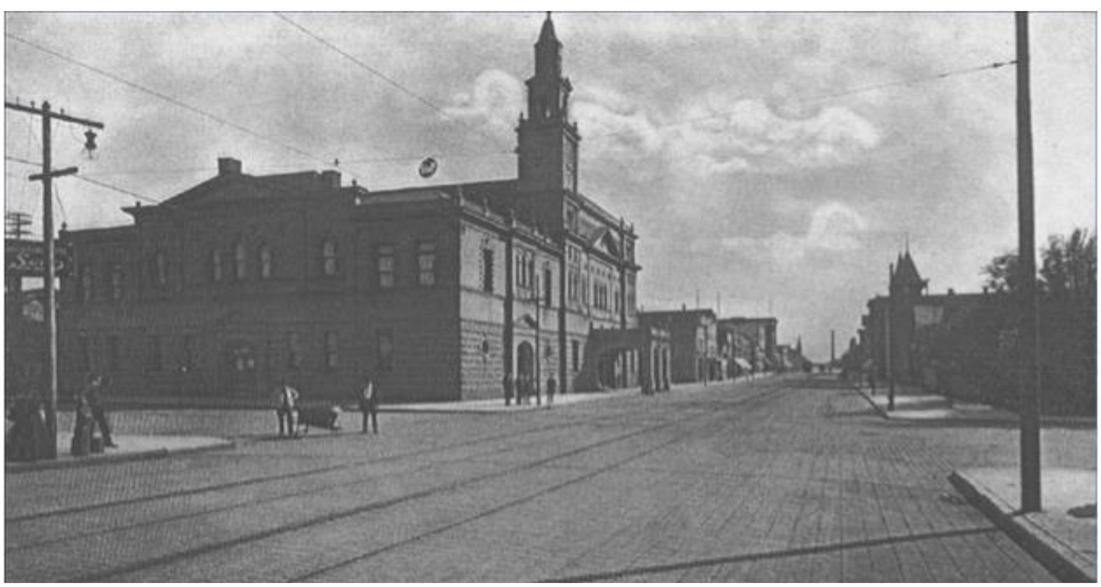

Figure 3. View of intersection of 6th and Elm Street in Calumet, MI, in 1910 (Mailloux et al., 2008)

Figure 4. View of 7th Street (left) and Portland (right) in 2013 (Forgave, 2013)

Figure 5. R.S. Blome granitoid pavement in Grand Forks, ND (Hoffbeck, 1990)

Figure 6. Belknap Place in San Antonio, TX (Taubert, 2014)

Table 1: European and U.S. experiences with two-lift concrete pavements (Berry et al., 2013; Tompkins et al., 2009; Cable et al., 2004; Vancura et al., 2009; Tompkins et al., 2010; Akkari and Izevbekhai, 2011; Debroux and Dumont, 2005; Rens et al., 2008; Bilec et al., 2010; Smiley, 2010; Wojakowski, 1998; Akkari and Izevbekhai, 2011)

	Year	Location	Highway/pavement name	Length (Km)	t_{top}/ t_{bottom} (mm)	Bottom-Lift Concrete	Top-Lift Concrete
European Experience	1989	Austria	Freeway A1	NA	40 / 210		
	1993	Austria	A1 near Eugendorf	NA	40 / 210	RCA	EAC
	1994	Austria	A1 near Traun	NA	60 / 160	PCC	EAC
	1999	Austria	A1 near Vorchdorf	NA	50 / 210	PCC	EAC
	2003	Belgium	N511	1.3	50 /150	CRCP	EAC
	2005	Belgium	E34 motorway	3.0	50 /175	CRCP	EAC
	2008	Germany	A6 Near Amberg	21	50 /250	PPC	EAC
	2004	France	Highway A71	NA	50 / 200	CRCP	EAC
	NA	Germany	Munich Airport	NA	140 / 250	PCC	EAC
	2000	Netherlands	N279, Near Veghel	17	90 / 180	JPCP	EAC
	1996	Germany	A93 motorway	13.5	70 / 190	PPC	EAC
		Germany	A99, Near Ottobrunn	NA	NA	NA	NA
U.S. Experience	1976	Iowa	U.S. 75	NA	75 / 175	Low cement content	
	1976	North Dakota	U.S. 2 b/w Rugby and Leeds	NA	NA	Local aggregate	Durable aggregate
	1977	Florida	U.S. 41	4.0	75 / 225	Low quality PCC	PCC
	1994	Michigan	I-75, NB	1.6	62 / 190	PCC	PCC
	1997	Kansas	K-96	Y	75 / 175	15% RAP, Local limestone	Durable aggregate
	2008	Kansas	I-70 in Saline County	8.0	40 / 300	Local aggregate	Durable aggregate
	2008	Pennsylvania	Mon-Fayette Expressway	NA	NA	NA	NA
	2010	Minnesota	I-94, Cell 72	0.144	75 /150	RCA, Local aggregate	PCC
	2012	Illinois	Tollway	6.75	NA	NA	NA
	2017	Texas	Frontage Road in Fort Bend	0.34	75/ 175	High-CoTE Aggregate	Low-CoTE Aggregate

POTENTIAL ADVANTAGES OF TWO-LIFT CONCRETE PAVEMENT

A two-lift concrete pavement system has several advantages. One major benefit is being able to use manufactured sands at higher percentages. Natural siliceous sand resources are being depleted, especially in the Dallas and Fort Worth districts, and hauling natural sand resources from surrounding districts and states is neither economical nor sustainable. As a result, several Departments of Transportation (DOTs) have permitted the use of manufactured sands at higher levels in their concrete paving specifications. However, faster surface polishing and lower workability are two primary obstacles encountered in concrete paving projects that use higher percentages of manufactured carbonate sands (Fowler and Rached, 2012). Surface polishing of concrete pavements results in lower surface texture, and consequently in lower skid resistance, at a much faster rate compared to natural sands, all of which affects the safety of commuters as well as the overall functional performance of the concrete pavements. Manufactured sands, on the other hand, create lower workability and reduce finishability of concrete mixtures, owing to the shape, texture, grading, and angularity of manufactured sands (Alqarni, 2013). Furthermore, the current Texas Department of Transportation (TxDOT) specifications require that fine aggregates have an acid insoluble residue of at least 60% for it to be used, and that effectively limits the use of manufactured sands to 40% or less in concrete paving. Unlike single-lift concrete pavements, with a two-lift pavement, the bottom-lift concrete layer can be composed of 100% manufactured sand for two reasons: First, the bottom lift is not exposed to traffic loading that would cause polishing problems, and second, the finishing requirements are not as strict as for the top lift. A comparison between a single-lift pavement with a thickness of 300 mm and a two-lift concrete pavement with top and bottom thicknesses of 70 and 230 mm, respectively, results in an overall reduction in natural sands (good quality sands) of 77% if the bottom lift contains 100% manufactured sand. Moreover, the reduction is further increased to 88% when the top lift uses blended sands (50% manufactured sand and 50% natural sand).

Another benefit of two-lift pavement is the use of high-CoTE aggregate in the bottom lift. The CoTE is defined as the change in length relative to the original length per degree change in temperature. In jointed concrete pavements, transverse joints are intended to accommodate temperature-induced contraction and expansion. However, concrete volume changes due to moisture and temperature variations in continuously reinforced concrete pavements (CRCPs) are controlled by longitudinal reinforcements to keep transverse cracks tightly closed. Nevertheless, CRCPs with high-CoTE aggregate in the Houston, Dallas, and Fort Worth districts have experienced a high level of distress, including early age transverse and random cracking, spalling, and punchouts (Siddiqui and Fowler, 2013). As a result, TxDOT has recently eliminated aggregates that produce concrete with a CoTE of 10×10^{-6} mm/mm/ºC or higher in concrete paving to overcome these problems. Generally, the CoTE values observed in concrete mixtures in the literature vary from 5.5 to 14.510×10^{-6} mm/mm/ºC (Naik et al., 2010; Siddiqui and Fowler, 2013).

Several researchers have indicated that the CoTE of aggregate is the most influencing parameter on the coefficient of expansion of concrete (Jahangirnejad et al., 2009; Mallela et al., 2005; Naik et al., 2010, 2006; Ndon and Bergeson, 1995; Olidis and Hein, 2004; Won, 2005). As opposed to single-lift concrete pavements, the use of high-CoTE aggregates in the bottom lift encapsulated by a low-CoTE aggregate in the top lift provides economic and sustainability advantages. A recent study indicated that the thermal gradient for concrete reduces to a point that makes it satisfactory to use high-CoTE aggregates in the bottom lift beginning at a depth of 76 mm below the surface (Yeon et al., 2013).

The use of RCA, RAP, or FRAP in concrete pavement has over the last few decades received considerable attention in the United States, including in Illinois, Florida, and Montana (Berry et al., 2013; Brand et al., 2012). A large number of experimental studies have indicated that concrete pavements created with RCA have achieved acceptable performance (Gress et al., 2009; Roesler et al., 2011; Wade et al., 1997; Yrjanson, 1989). One primary concern with recycled materials is the long-term durability performance, which is a function of the replacement level, water-to-cementitious-material ratio, concrete age, and moisture (Yehia et al., 2015). Even though recycled aggregate concrete typically results in lower mechanical properties (Brand et al., 2014), lower abrasion and ingress resistance (Thomas et al., 2013), and lower fresh concrete properties (Qasrawi and Marie, 2013), it can generally be produced to meet standard aggregate quality and grading requirements if adequate replacement level, proper care, and process control are taken into account. The incorporation of RCA, RAP, and/or FRAP into two-lift concrete pavement provides economic, environmental, and sustainability advantages, and offers practical solutions. First, the top lift usually contains high-quality aggregates, which eliminates surface-related durability issues. Second, the lower strengths achieved when such recycled materials are used in the bottom lift still meets concrete paving specifications. In the context of the feasibility of two-lift pavement with RCA and FRAP, (Brand et al., 2014) showed although the mechanical properties of concrete cylinders and beams with FRAP and RCA materials were negatively affected compared to the control specimens, the concrete slabs demonstrated superior flexural performance.

The potential for utilizing higher quantities of supplementary cementitious materials, such as fly ashes Class F or Class C, and a lesser volume of portland cement for two-lift concrete pavements, offers economic, environmental, and long-term durability benefits. The effect of fly ash on the performance of concrete has been extensively investigated, and several laboratory studies have revealed that Class F fly ash improved freeze-thaw resistance, had a low permeability to chloride ions, had no ASR expansion (Alasali and Malhotra, 1991; Giaccio and Malhotra, 1988; Langley et al., 1989; Malhotra, 1990), and adequate workability (Siddique, 2004). Furthermore, the strength characteristics of concrete containing fly ash are generally lower at early ages and are a function of the type of ash, the replacement level, and the water-to-cementitious-material ratio (Atiş, 2002; Naik et al., 1994; Siddique, 2004). In spite of these advantages, abrasion resistance (Naik et al., 1994; Yen et al., 2007), deicer-salt scaling resistance, carbonation resistance, and strength gain (Thomas, 2007) seem to reduce with a higher volume of fly ash. To overcome these potential limitations, a higher volume of fly ash can be used in the lower lift since it is protected by high-quality concrete in the top lift.

POTENTIAL DISADVANTAGES OF TWO-LIFT CONCRETE PAVEMENT

There are a few potential challenges associated with two-lift concrete pavement to be addressed. First, developing a cost-effective concrete mixture design in the lower lift with higher levels of recycled materials or SCMs is essential to meet the adopted specifications. For instance, (Texas Department of Transportation, 2014) requires that the concrete compressive strengths at 7 and 28 days be at least 22 and 28 MPa, respectively. Second, timing and coordinating during the construction of two-lift concrete pavement is crucial to achieving proper performance. This involves placing the top lift within 30 to 90 minutes after the placement of the lower lift to achieve a good bond and having continuous supervision, including the use of colored paint and flags on the delivery trucks, to eliminate the risk of pouring concrete into the wrong paving machines. Third, two-lift concrete pavement normally requires two batch plants, two spreaders, two slip form pavers, and extra labor crews, all of which increase the cost of the paving project. However, the additional costs can be offset if local aggregates, recycled materials, and optimized concrete mixtures are used.

COST ANALYSIS OF TWO-LIFT CONCRETE PAVEMENT

The design and construction requirements of two-lift pavement are the same as conventional concrete pavement with respect to preparing the subgrade, base, and subbase, as well as ensuring adequate mechanical properties and reinforcement percentages. The SHRP2 carried out a detailed cost analysis for the U.S. Highway 14 project, which was 31.4 km long and 8.3 m wide, with a thickness of 230 mm and was constructed near Waseca, Minnesota, where good quality aggregates were not available (Rao et al., 2013). The conventional single-lift concrete pavement bid was compared with the expected costs if the project were to be constructed with two-lift concrete pavement. The conventional concrete pavement was assumed to be made with high-quality aggregate for the full depth, which was a two-hour round-trip haul from the project site. On the other hand, the top lift of the two-lift concrete pavement of 75 mm was designed to have high-quality aggregate, whereas the bottom lift of 150 mm was made with locally available recycled aggregate and 60% fly ash replacement. The comparison was made in terms of paving operations, aggregates, equipment, and crews. The U.S. Highway 14 project utilized 68,810 m^3 of concrete, of which 61,165 $m^3$was for paving and 7646 m^3 was for crossroads and ramps. The pavement systems showed comparable costs, with a difference of 0.7%, or $44,800. Paving costs increased $0.86 per m^2 for the two-lift concrete compared to that of the single lift due to the extra paver, belt placer, and large crew size required for the two-lift pavement. Nevertheless, the savings from concrete aggregates in the two-lift pavement were $2.92/ m^3, which were achieved by using recycled aggregate in the bottom lift and minimizing the trucking costs. Had this project been subjected to heavier traffic loading, the bottom lift would have been thicker and the cost difference would have been in favor of the two-lift pavement. It is generally believed that as contractors progress further up the learning curve, the labor productivity will increase and the equipment operations cost will likely decrease, resulting in more savings for two-lift pavement.

CONCLUSION

For many applications and locations, the use of two-lift concrete pavement is not only cost-effective but is also an environmentally sustainable approach. In some regions of the world, where local aggregate resources have a high volume of byproducts, recycled materials might not be allowed to be used for the entire depth of concrete pavements, in accord with some international standards. Such materials are nevertheless allowed to be used in two-lift concrete pavement in the bottom lift at certain replacement levels. It is expected that the additional costs resulting from the use of two concrete plants, two slip-form pavers, and extra labor and hauling trucks are offset by being able to use local resources. Moreover, these additional costs can further be minimized if two-lift paving equipment and techniques are further developed and contractors develop more experience with the process.

REFERENCES:

Akkari, A., Izevbekhai, B., 2011. Composite pavements at MnROAD: cells 70, 71 and 72 construction report and early performanceevaluation.

Alasali, M.M., Malhotra, V.M., 1991. Role of concrete incorporating high volumes of fly ash in controlling expansion due to alkali-aggregate reaction. Mater. J. 88, 159–163.

Alqarni, A.S., 2013. Quantifying the characteristics of fine aggregate using direct and indirect test methods (Master's Thesis).

Atiş, C.D., 2002. High volume fly ash abrasion resistant concrete. J. Mater. Civ. Eng. 14, 274–277. https://doi.org/10.1061/(ASCE)0899-1561(2002)14:3(274)

Berry, M., Stephens, J., Bermel, B., Hagel, A., Schroeder, D., 2013. Feasibility of reclaimed asphalt pavements as aggregate in portland cement concrete (No. FHWA/MT-13-009/8207). Montana Department of Transportation.

Bilec, M.M., Marriott, J., Padilla, M.F., Snyder, M., 2010. Market analysis of construction materials with recommendations for the future of the industry (No. FHWA-PA-2010-004-PIT016).

Brand, A., Amirkhanian, A., Roesler, J., 2014. Flexural capacity of full-depth and two-lift concrete slabs with recycled aggregates. Transp. Res. Rec. J. Transp. Res. Board 2456, 64–72. https://doi.org/10.3141/2456-07

Brand, Roesler, J.R., Al-Qadi, I.L., Shangguan, P., 2012. Fractionated reclaimed asphalt pavement (FRAP) as a coarse aggregate replacement in a ternary blended concrete pavement (No. ICT-12-008). Illinois Center for Transportation.

Cable, J.K., Frentress, D.P., Williams, J.A., 2004. Two-lift portland cement concrete pavements to meet public needs. Iowa State University, Ames: Center for Transportation Research and Education.

Darter, M., 1992. Report on the 1992 U.S. tour of European concrete highways (No. FHWA-SA-93-012). Federal Highway Administration: US Department of Transportation.

Debroux, R., Dumont, R., 2005. Twin-layer continuously reinforced concrete pavement on the N511 at Estaimpuis (Belgium): an investigation of the optimization of surface characteristics. Presented at the Eighth International Conference on Concrete Pavements.

Fowler, D., Rached, M., 2012. Polish resistance of fine aggregates in portland cement concrete pavements. Transp. Res. Rec. J. Transp. Res. Board 2267, 29–36. https://doi.org/10.3141/2267-03

Giaccio, G.M., Malhotra, V.M., 1988. Concrete incorporating high volumes of ASTM Class F fly ash. Cem. Concr. Aggreg. 10, 88–95. https://doi.org/10.1520/CCA10088J

Gress, D., Snyder, M., Sturtevant, J., 2009. Performance of rigid pavements containing recycled concrete aggregate. Transp. Res. Rec. J. Transp. Res. Board 99–107. https://doi.org/10.3141/2113-12

Hall, K.T., Dawood, D., Vanikar, S., Tally Jr, R., Cackler, T., Correa, A., Deem, P., Duit, J., Geary, G.M., Gisi, A.J., Hanna, A.N., Kosmatka, S., Rasmussen, R.O., Tayabji, S., Voigt, G., 2007. Long-life concrete pavements in Europe and Canada (No. FHWA-PL-07-027). U.S. Department of Transportation: Federal Highway Administration.

Hoffbeck, S., 1990. Granitoid pavement in Grand Fork, North Dakota. Grand Fork Historic Preservation Connision.

Iowa State College, I.S.U., 1919. The Iowa Engineer. New York Public Library.

Jahangirnejad, S., Buch, N., Kravchenko, A., 2009. Evaluation of coefficient of thermal expansion test protocol and its impact on jointed concrete pavement performance. Mater. J. 106, 64–71.

Langley, W.S., Carette, G.G., Malhotra, V.M., 1989. Structural concrete incorporating high volumes of ASTM class fly ash. Mater. J. 86, 507–514.

Mailloux, L., Peterson, K., Ellis, K., King, M., Van Dam, T., Scarlett, T., 2008. The granitoid concrete pavement of Calumet, Michigan- over one hundred years of service. Presented at the 9th international conference on concrete pavements, International Society for Concrete Pavements, San Francisco California, United States, pp. 346–363.

Malhotra, V.M., 1990. Durability of concrete incorporating high-volume of low-calcium (ASTM class F) fly ash. Cem. Concr. Compos. 12, 271–277.

Mallela, J., Abbas, A., Harman, T., Rao, C., Liu, R., Darter, M., 2005. Measurement and significance of the coefficient of thermal expansion of concrete in rigid pavement design. Transp. Res. Rec. J. Transp. Res. Board 38–46.

Moorefield, C., Voshell, J., 1915. Portland cement concrete pavements for country roads (No. 249). US Department of Agriculture.

Naik, T.R., Chun, Y., Kraus, R.N., 2006. Investigation of concrete properties to support implementation of the new AASHTO pavement design guide.

Naik, T.R., Kraus, R.N., Kumar, R., 2010. Influence of types of coarse aggregates on the coefficient of thermal expansion of concrete. J. Mater. Civ. Eng. 23, 467–472.

Naik, T.R., Singh, S.S., Hossain, M.M., 1994. Abrasion resistance of concrete as influenced by inclusion of fly ash. Cem. Concr. Res. 24, 303–312.

Ndon, U.J., Bergeson, K.L., 1995. Thermal expansion of concretes: case study in Iowa. J. Mater. Civ. Eng. 7, 246–251.

Olidis, C., Hein, D., 2004. Guide for the mechanistic-empirical design of new and rehabilitated pavement structures materials characterization is your agency ready?, in: 2004 Annual Conference of the Transportation Association of Canada.

Portland Cement Association, P.C.A., 1915. Facts everyone should know about concrete roads. Association of American Portland Cement Manufacturers.

Qasrawi, H., Marie, I., 2013. Towards better understanding of concrete containing recycled concrete aggregate. Adv. Mater. Sci. Eng. 2013, 8. https://doi.org/10.1155/2013/636034

Rao, S., Darter, M., Tompkins, D., Vancura, M., Khazanovich, L., Signore, J., Coleri, E., Wu, R., Harvey, J., Vandenbossche, J., Strategic Highway Research Program, Strategic Highway Research Program Renewal Focus Area, Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, 2013. Composite Pavement Systems, Volume 2: PCC/PCC Composite Pavements. Transportation Research Board, Washington, D.C. https://doi.org/10.17226/22645

Rens, L., Keymeulen, H., Van Wijnendaele, I., 2008. A double-layered CRCP: experiences on the E34 near Antwerp (Belgium). Presented at the 9th International Conference on Concrete Pavements.

Roesler, J., Huntley, J., Amirkhanian, A., 2011. Performance of continuously reinforced concrete pavement containing recycled concrete aggregates. Transp. Res. Rec. J. Transp. Res. Board 2253, 32–39. https://doi.org/10.3141/2253-04

Siddique, R., 2004. Performance characteristics of high-volume Class F fly ash concrete. Cem. Concr. Res. 34, 487–493. https://doi.org/10.1016/j.cemconres.2003.09.002

Siddiqui, M.S., Fowler, D.W., 2013. Optimizing the COTE of concrete by blending high and low COTE aggregates to meet TxDOT limit, in: Green Streets, Highways, and Development 2013: Advancing the Practice. pp. 125–134.

Smiley, D.L., 2010. Fifteen year performance review of Michigan's European concrete pavement (No. R-1538). Michigan Department of Transportation.

Smith, K.D., Wade, M.J., Peshkin, D.G., Khazanovich, L., Yu, H.T., Darter, M.I., 1998. Performance of concrete pavements. volume II: evaluation of inservice concrete pavements (No. FHWA-RD-95-110).

Snell, L.M., Snell, B.G., 2002. Oldest concrete street in the United States. Concr. Int. 24, 72–74.

Taubert, D., Prusinski, J.R., 2014. Narrative history of Belknap Place oldest existing concrete road in Texas (1914) San Antonio, Texas.

Texas Department of Transportation, 2014. Standard specifications for construction and maintenance of highways, streets, and bridges.

Thomas, C., Setién, J., Polanco, J.A., Alaejos, P., Sánchez de Juan, M., 2013. Durability of recycled aggregate concrete. Constr. Build. Mater. 40, 1054–1065. https://doi.org/10.1016/j.conbuildmat.2012.11.106

Thomas, M., 2007. Optimizing the Use of Fly ash in Concrete. Portland Cement Association, Skokie, IL.

Tompkins, D., Khazanovich, L., Darter, M., Fleischer, W., 2009. Design and construction of sustainable pavements: Austrian and German two-layer concrete pavements. Transp. Res. Rec. J. Transp. Res. Board 2098, 75–85. https://doi.org/10.3141/2098-08

Tompkins, D., Khazanovich, L., Darter, M.I., 2010. 2008 survey of European composite pavements.

Vancura, M., Khazanovich, L., Tompkins, D., 2009. Reappraisal of recycled concrete aggregate as coarse aggregate in concretes for rigid pavements. Transp. Res. Rec. 2113, 149–155.
Wade, M.J., Cuttell, G.D., Vandenbossche, J.M., Yu, H.T., Smith, K.D., Snyder, M.B., 1997. Performance of concrete pavements containing recycled concrete aggregate (No. FHWA-RD-96-164). University of Minnesota, Twin Cities.
Wojakowski, J., 1998. High performance concrete pavement (No. FHWA-KS-98/2). Kansas Department of Transportation.
Won, M., 2005. Improvements of testing procedures for concrete coefficient of thermal expansion. Transp. Res. Rec. J. Transp. Res. Board 23–28.
Yehia, S., Helal, K., Abusharkh, A., Zaher, A., Istaitiyeh, H., 2015. Strength and durability evaluation of recycled aggregate concrete. Int. J. Concr. Struct. Mater. 9, 219–239. https://doi.org/10.1007/s40069-015-0100-0
Yen, T., Hsu, T.-H., Liu, Y.-W., Chen, S.-H., 2007. Influence of class F fly ash on the abrasion–erosion resistance of high-strength concrete. Constr. Build. Mater. 21, 458–463. https://doi.org/10.1016/j.conbuildmat.2005.06.051
Yeon, J.H., Choi, S., Won, M.C., 2013. In situ measurement of coefficient of thermal expansion in hardening concrete and its effect on thermal stress development. Constr. Build. Mater., 25th Anniversary Session for ACI 228 – Building on the Past for the Future of NDT of Concrete 38, 306–315. https://doi.org/10.1016/j.conbuildmat.2012.07.111
Yrjanson, W.A., 1989. Recycling of Portland cement concrete pavements. Transportation Research Board.