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EFFECT OF MIXTURE PROPORTIONS ON COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

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ABSTRACT

This paper summarizes recent research conducted by the UWM Center for By-Products Utilization on the coefficient of thermal expansion (CTE) of concrete. A standard concrete mixture specified by the Wisconsin Department of Transportation was used as the basis for all other concrete mixtures. Coarse aggregates obtained from 15 different sources were investigated. They were glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt.

From the types of coarse aggregates tested, the concrete made with quartzite had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F). The CTE of concrete mixtures made with dolomite from the five sources was approximately the same, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F).

Keywords: coefficient of thermal expansion, concrete, mechanistic-empirical design, pavement, splitting tensile strength.

1. INTRODUCTION

The National Cooperative Highway Research Program (NCHRP) of the US through a research and development project, Project 1-37A, developed a pavement design procedure that is based on a combination of engineering mechanics and empirical methods [ARA 2004]. One of the advantages of such a method is that the pavement behavior is predicted based on actual material properties and response to stresses. Most of the earlier AASHTO (American Association of State Highway and Transportation Officials) design guides for pavement design were based on the performance of a pavement section that was subjected to approximately 2 million cycles of axle loads. Currently, many pavement designs require over 100 million load cycles over the design life of the pavement. Clearly an improvement in the reliability of the design was warranted. Therefore, the NCHRP 1-37A pavement design procedure was developed to estimate the long-term pavement behavior using a more rational method. This design procedure is expected to evolve in the future to a design based purely on engineering mechanics. The current state-of-the-art limits the current design guide to a combination of mechanics and empirical methods.

Many departments of transportation (DOTs) in the US have started to review the design procedures outlined in the NCHRP design guide [ARA 2004] since the design procedure is expected to be officially adopted by AASHTO in the near future. In order to implement the mechanistic-empirical design procedure and take advantage of the potential cost savings, the Wisconsin Department of Transportation (WisDOT) identified material properties required for the design of rigid pavement (concrete pavement) that had not been previously measured by the WisDOT. The two properties evaluated in this project were the indirect tensile strength as measured by AASHTO T 198, “Splitting Tensile Strength of Cylindrical Concrete Specimens,” and the coefficient of thermal expansion (CTE), measured by a AASHTO provisional test standard TP 60, “Coefficient of Thermal Expansion of Hydraulic Cement Concrete.” The WisDOT has also reported that the design of the thickness of the pavement, and the predicted performance of the pavement are very sensitive to changes in the tensile strength and the CTE. The focus of this project was to develop input values for the new pavement design procedure for concrete pavement construction in Wisconsin. This project was conducted by the UWM Center for By-Products Utilization (UWM-CBU) to document and evaluate the concrete containing specified Wisconsin materials for splitting tensile strength and CTE. The sources of cement, GGBFS (ground granulated blast-furnace slag), fly ash, and aggregate were selected in consultation with the WisDOT. This paper presents the portion of research findings on the CTE of concrete made with various types and sources of coarse aggregates.

2. LITERATURE REVIEW

2.1 MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

The NCHRP 1-37A pavement design guide [ARA 2004] was developed to estimate the long-term pavement behavior by using a combination of engineering mechanics and empirical methods. This approach to a mechanistic-empirical design of new and rehabilitated pavement structures considers traffic, climate, subgrade, and existing pavement condition, as well as material properties in order to predict pavement responses to stresses and temperature variations, and to predict pavement failures. Three levels of designs are specified for the method, each with different expected accuracies. Level 1 design produces the highest accuracy and requires that all material properties be established through laboratory and field testing. The splitting tensile strength at the ages of 7, 14, 28, and 90 days are required for Level 1 design. Compressive strength is not required for Level 1 design; but in Level 2 design and Level 3 design, which are design levels of lower accuracy, compressive strength can be used to estimate the modulus of elasticity, flexural strength, and splitting tensile strength of the concrete. Level 2 design provides an intermediate accuracy and would produce results similar to earlier editions of the AASHTO pavement design guides. Level 2 design uses some of the specific material properties through relationships with other known parameters, for example, estimating splitting tensile strength from actual test data of compressive strength. Level 3 design would produce the lowest accuracy. The material properties in Level 3 design would be estimated from historical data, similar estimates, the 28-day flexural strength, and/or the 28-day compressive strength.

In order for the mechanistic-empirical design to produce a rational design, the material properties must be evaluated that are used to predict the material responses to stresses and variations in temperature (climate), and to predict failures.

DOTs have also begun activities for implementation of the NCHRP 1-37A pavement design guide. Presentations have been made on the use of the design guide, sensitivity analysis, and design examples [Galal and Chebab 2005, Hall and Beam 2005, Mallela et al. 2005, Uzan et al. 2005, Won 2005, Yang et al. 2005].

2.2 COEFFICIENT OF THERMAL EXPANSION (CTE)

The coefficient of thermal expansion (CTE) of concrete has been shown to have a significant impact on the expected pavement durability when used in the mechanistic-empirical pavement design [Walls 2004]. A sensitivity analysis was conducted on a theoretical pavement design entered into the computer program. Various design parameters were revised including climate, pavement thickness, flexural strength, shoulder design, joint spacing, traffic conditions, lane width, and various concrete material properties. The parameter that had the most effect on cracking, joint faulting, and IRI (International Ride Index) was a change in the aggregate type from limestone with a CTE of 9×10^{-6}/°C to a siliceous gravel with a CTE of 12×10^{-6}/°C. When the aggregate type was changed from limestone to the siliceous gravel with all other parameters the same, the cracking of the slab increased over five times, the joint faulting increased by 1.5 times, and the IRI increased by 60%. When the flexural strength (Modulus of Rupture (MOR)) of the slab was reduced, the effect on joint faulting and IRI was minimal, while the amount of cracking in a low-MOR concrete increased by approximately four times. This shows that the flexural strength and the CTE are very important factors when using the new pavement design guide.

The CTE of various types of aggregates in concrete have been evaluated since the 1940s [Parsons and Johnson 1944]. Parsons and Johnson [1944] reported on the CTE of concrete using numerous types of aggregates. The CTE of dolomite varied between 6.7 to 8.6 × 10^{-6}/°C, granite 5.9 to 9.2 × 10^{-6}/°C, basalt 4.3 to 7.4 × 10^{-6}/°C, and quartzite 7.0 to 12.2 × 10^{-6}/°C. Parsons and Johnson suggested that the aggregates that had significantly different CTEs than the cement paste (10 to 16 × 10^{-6}/°C), may cause durability problems in concrete. Mindess and Young [1981] also reported that the CTE of concrete varies according to the mixture proportions and aggregates used. Only minor variations in the CTE of mortar occurred for the normal ranges of cementitious materials (water to cementitious materials ratio of 0.4 to 0.6); therefore, changes in the mortar composition should not have a significant effect on the CTE of concrete. Mehta also reported that the highest expansion occurred for some natural gravels, sandstone, and quartzite [Mehta and Monteneiro 1993].

Naik and Singh [1992] reported that mechanical behavior of concrete can be modeled by using available models for composites. Emmanuel and Hulsey [1977] have shown that the CTE could be estimated by an empirical relationship between the thermal expansion of each component of concrete (cement paste, coarse aggregate, fine aggregate) and considering the volume fraction of each component in the concrete. Using this relationship, and considering the age of the concrete and the degree of saturation, they estimated the CTE of concrete and compared it with experimental results. The CTE estimated by the empirical relationship was found to be close to actual experimental values. A study by Ndon and Bergeson [1995] also compared three different methods for obtaining the CTE: a laboratory test, field measurements, and the empirical relationship from Emmanuel and Hulsey [1977]. Two concrete bridge structures were evaluated, one containing limestone and the other containing gravel aggregate. CTE results obtained using all three methods were found to be in close agreement.

Ziegeldorf, et al. [1978] also tested two types of aggregate in concrete, crushed limestone and river gravel. It was concluded that fine aggregate had a minor effect on CTE of concrete, while the coarse aggregate had a significant effect on CTE. Based on tests conducted in the study, it was concluded that the equation used to predict CTE proposed by Emmanuel and Hulsey [1977] did not always result in a reliable CTE. The CTE determined by simply using the product of the volume and CTE of each component did not adequately account for restraint of expansion within the concrete matrix. Another relationship was supported [Yang et al. 2005], but only when the composition of the aggregates was uniform.

A recent study [Hossain et al. 2006] compared the estimated CTE of concrete and the CTE of concrete measured in accordance with AASHTO TP 60. The estimated CTE values, calculated as weighted averages of the CTEs of aggregates and cement paste, were 10 to 30% higher than the measured CTE values. The study also reported that the CTE of concrete had a significant effect on the predicted percent of slabs cracked.

The moisture condition of the concrete was found to affect the CTE of concrete. For example, the CTE of a concrete containing gravel in an air-dried condition when cooling was 8.1 × 10^{-6}/°C, while the CTE of the concrete in a saturated condition when cooling was 6.1 × 10^{-6}/°C.

The test method used for measurement of the CTE for this project is the AASHTO test procedure TP 60. Several DOTs in the U.S. have already started evaluating concrete pavement using this test procedure. A study was conducted by the University of Texas for the Texas Department of Transportation using the proposed AASHTO TP 60 procedure [Won 2005]. This study found that the age of concrete or the rate of heating or cooling did not affect the CTE. Two different sizes of test cylinders were evaluated, 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.). The change in the cylinder size also did not have a significant effect on the CTE. The coarse aggregate content was found to have a significant impact on the CTE, approximately a 0.045 × 10^{-6}/°C change for each percent change in the coarse aggregate volume. The aggregate type also had a significant impact on the CTE of concrete. Crushed limestone (11 sources) and gravel (21 sources) were evaluated in many concrete mixtures. Limestone showed minimal variation in CTE between sources, while the CTE for gravel sources varied from 8.1 to 13.0 × 10^{-6}/°C. Using the equipment specified by AASHTO TP 60 to obtain the CTE, problems were reported in repeatability and stability of the readings at 10°C and 50°C [Won 2005]. A regression analysis of the CTE of concrete during heating and cooling was recommended as an alternative test method to obtain the CTE while using the AASHTO apparatus.

There were also favorable reports [Hossain et al. 2006, Lingannagari et al.] about the equipment and test procedure of the AASHTO TP 60 for measuring the CTE of concrete.

According to the chapter on material characterization (Chapter 2. Materials, in Part 2. Design Inputs) in the mechanistic-empirical design guide [ARC 2004], at Input Level 1, the CTE of concrete is measured using AASHTO TP 60. At Input Level 2, CTE of concrete is estimated using a weighted average of the CTE values of aggregates and hardened cement paste based on the relative volumes of the constituents. However, the ranges of CTE of aggregates provided in the design guide are quite wide, making it difficult to make a reasonably accurate estimation of the CTE of concrete. At Input Level 3, CTE of concrete is estimated based on overall historical averages.

3. RESEARCH SIGNIFICANCE

The overall objective of this project was to provide material properties to be used for input into a mechanistic-empirical design procedure for concrete pavements. The use of the mechanistic-empirical design basis for design of concrete pavements is expected to provide increased reliability of pavement structures and to provide a basis for the prediction of service life, and how the pavement design parameters will affect various pavement failure modes including cracking, faulting, and IRI (International Roughness Index).

4. EXPERIMENTAL PROGRAM

4.1 WORK PLAN USED

In order to meet the requirements of the WisDOT and determine the effect of the aggregate source on the splitting tensile strength and CTE of concrete, a base mixture with one fixed source of cement and one fixed source of fly ash was selected and the aggregate source was then varied for each mixture. In total, 15 mixtures were evaluated for testing for effects of aggregate sources. Since most concrete pavement mixtures produced in Wisconsin include fly ash, the base mixture that was approved for testing was the WisDOT Grade A-FA (70% cement plus 30% Class C fly ash) mixture. These 15 concrete mixtures were made using cement from Source 1 (Cement 1) and fly ash from Source 1 (Fly ash 1).

Initially, the research team proposed a maximum size of 19 mm (0.75 in.) for all the aggregates selected for the project. This was a result of the requirements of the AASHTO TP 60 test procedure that specifies a 100-mm (4-in.) diameter × 200-mm (8-in.) long cylindrical specimen for determining the CTE of concrete. Previous research on the CTE had shown that using a 100 × 200 mm (4 × 8 in.) cylinder vs. a 150 × 300 mm (6 × 12 in.) cylinder did not affect the CTE [Won 2005].

Based on the comments provided by the WisDOT, the concrete mixtures produced for this project used a blend of coarse aggregate sizes, 60% ASTM C 33 No. 67 stone (19 to 5 mm [0.75 to 3/16 in.]) and 40% ASTM C 33 No. 4 stone (38 to 19 mm [1.5 to 0.75 in.]). WisDOT indicated that the 100 × 200 mm (4 × 8 in.) cylinders could still be cast using the aggregate blend. The compressive strength, splitting tensile strength, and coefficient of thermal expansion (CTE) of concrete were evaluated using 100 × 200 mm (4 × 8 in.) cylinders.

4.2 MATERIALS

ASTM Type I portland cement (ASTM C 150) was used in this work. ASTM Class C fly ash (ASTM C 618) was obtained from the We Energies' Pleasant Prairie Power Plant (P4). Natural sand was used as fine aggregate. The sand met the requirements of ASTM C 33.

In total, coarse aggregates from 15 sources were used in this research project: glacial gravel from six sources, dolomite from five sources, quartzite, granite, diabase, and basalt. Table 1 contains a summary of the coarse aggregate sources collected in consultation with WisDOT.

Table 1. Types and Sources of Coarse Aggregates Used

Aggregate designation	Aggregate type	County in Wisconsin, USA
Gvl1	Glacial Gravel – Lake Michigan Lobe	Racine
Gvl2	Glacial Gravel – Lake Michigan / Green Bay Transition	Manitowoc
Gvl3	Glacial Gravel – South End of Green Bay Lobe	Rock
Gvl4	Glacial Gravel – Central Green Bay Lobe	Portage
Gvl5	Glacial Gravel – Wisconsin Valley Lobe	Lincoln
Gvl6	Glacial Gravel – Chippewa River Gravel	Barron
Qtz	Baraboo Quartzite	Columbia
Gnt	Granite	Wood
Dbs	Diabase	Marathon
Bst	Basalt Traprock	Polk
Dlm1	Niagara Dolomite	Milwaukee
Dlm2	Galena Dolomite	Grant
Dlm3	Galena-Platteville Dolomite	Outagami
Dlm4	Prairie Du Chien Dolomite – SW Wisconsin	Crawford
Dlm5	Prairie Du Chien Dolomite – NE Wisconsin	Waupaca

4.3 SPECIMEN PREPARATION AND TEST METHODS

Test specimens of concrete were prepared and cured in accordance with the ASTM Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (C 192). The concrete mixer used in this research was an electrical power driven, revolving drum, tilting mixer. The cast specimens were removed from their molds 24 ± 4 hours after casting. The demolded specimens were moist cured in a moist room at a temperature of 23 ± 2°C (73 ± 3.5°F) and a relative humidity of not less than 95%.

The tests methods used to determine the properties of fresh concrete were as follows: ASTM C 143 for slump, ASTM C 138 for density, ASTM C 231 for air content by the pressure method, and ASTM C 1064 for concrete temperature. The test methods, specimens, and ages used for the testing of hardened concrete were as follows: ASTM C 39 for compressive strength by testing three 100 × 200 mm (4 × 8") cylinders at each test age of 7, 14, 28, and 90 days; AASHTO TP 60-00 for coefficient of thermal expansion by testing three 100 × 200 mm (4 × 8") cylinder at 28 days.

Fig. 1 shows the apparatus for coefficient of thermal expansion (CTE) of concrete used in this research.

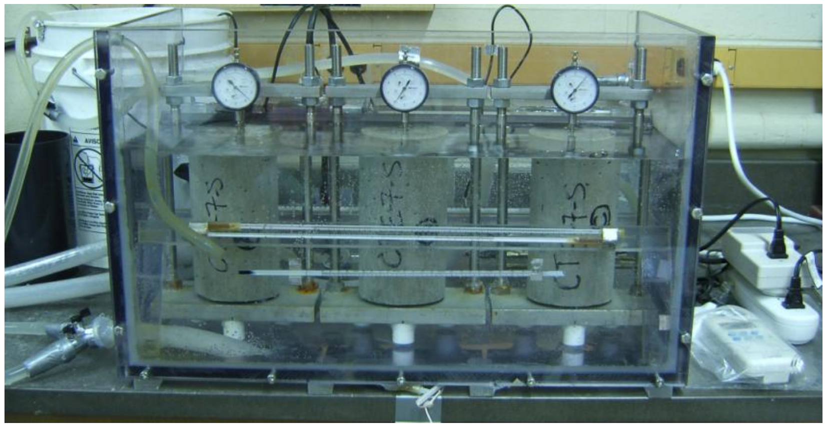

Fig. 1. Test apparatus for coefficient of thermal expansion (CTE) of concrete

5. MIXTURE PROPORTIONS, TEST RESULTS, AND DISCUSSION

5.1 MIXTURE PROPORTIONS

Mixture proportions were based on the proportions for WisDOT concrete Grade A-FA (using 70% cement and 30% Class C fly ash). Fine aggregate constituted 35% of the total aggregate in a concrete mixture. Following the direction from the WisDOT for this project, the coarse aggregate used was a blend of 60% ASTM C 33 No. 67 stone (19 to 5 mm [0.75 to 3/16 in.]) and 40% ASTM C 33 No. 4 stone (38 to 19 mm [1.5 to 0.75 in.]).

Fifteen concrete mixtures were evaluated for testing for effects of aggregate sources on the CTE of concrete. Since most concrete pavement mixtures produced in Wisconsin include fly ash, the base mixture that was approved for testing was the WisDOT Grade A-FA mixture. These 15 concrete mixtures were made using cement from Source 1 (Cement 1) and fly ash from Source 1 (Fly ash 1).

The mixture proportions and fresh properties of concrete mixtures are given in Tables 2 and 4. In most of the cases, the water-cementitious ratio (W/Cm) was 0.40, which was the design W/Cm. The W/Cm of several concrete mixtures varied by 0.01 or 0.02 (ranged from 0.38 to 0.41). The slump of concrete mixtures ranged from 25 to 105 mm (1 to 4 in.). The air content ranged from 4.8 to 7.9%.

Table 2. Mixture Proportions and Fresh Properties of Concrete Made With Gravel from Different Sources

Mixture Designation	Gvl1-c1-f1	Gvl2-c1-f1	Gvl3-c1-f1	Gvl4-c1-f1	Gvl5-c1-f1	Gvl6-c1-f1
Laboratory mixture designation	5	8	4	12	13	14
Cement, Lafarge I (kg/m^3)	236	241	232	241	239	238
Class C fly ash, Pleasant Prairie (kg/m^3)	102	104	100	104	103	103
Grade 120 GGBFS, Lafarge (kg/m^3)	0	0	0	0	0	0
Water (kg/m^3)	135	138	133	138	137	136
Fine aggregate, SSD (kg/m^3)	652	664	641	664	661	657
ASTM C 33 No. 67 coarse aggregate, 19 to 5 mm, SSD (kg/m^3)	729	737	719	738	735	732
ASTM C 33 No. 4 coarse aggregate, 38 to 19 mm, SSD (kg/m^3)	486	491	477	491	489	487
Water-reducing admixture (L/m^3)	0.18	0.17	0.05	0.05	0.08	0.07
Air-entraining admixture (L/m^3)	0.93	1.41	0.96	1.49	1.07	0.98
Water-cementitious ratio, W/Cm	0.40	0.40	0.40	0.40	0.40	0.40
Slump (mm)	80	80	70	75	75	105
Air content (%)	5.9	6.4	6.1	5.4	5.8	5.2
Air temperature (°C)	22	22	23	22	22	22
Concrete temperature (°C)	21	20	21	22	22	22
Density (kg/m^3)	2340	2370	2300	2380	2360	2350

Table 3. Mixture Proportions and Fresh Properties of Concrete Made With Quartzite, Granite, Diabase, or Basalt

Mixture Designation	Qtz-c1-f1	Gnt-c1-f1	Dbs-c1-f1	Bst-c1-f1
Laboratory mixture designation	1	10	11	15
Cement, Lafarge I (kg/m^3)	233	229	248	244
Class C fly ash, Pleasant Prairie (kg/m^3)	101	99	107	105
Grade 120 GGBFS, Lafarge (kg/m^3)	0	0	0	0
Water (kg/m^3)	130	134	143	140
Fine aggregate, SSD (kg/m^3)	644	633	685	673
ASTM C 33 No. 67 coarse aggregate, 19 to 5 mm, SSD (kg/m^3)	712	701	756	743
ASTM C 33 No. 4 coarse aggregate, 38 to 19 mm, SSD (kg/m^3)	475	465	504	494
Water-reducing admixture (L/m^3)	0.32	0.77	0.15	0.05
Air-entraining admixture (L/m^3)	1.93	1.66	1.14	2.35
Water-cementitious ratio, W/Cm	0.39	0.41	0.40	0.40
Slump (mm)	50	75	30	55
Air content (%)	6.1	7.9	4.8	6.4
Air temperature (°C)	22	22	21	21
Concrete temperature (°C)	21	21	21	21
Density (kg/m^3)	2300	2260	2440	2400

Table 4. Mixture Proportions and Fresh Properties of Concrete Made With Dolomite from Different Sources

Mixture Designation	Dlm1-c1-f1	Dlm2-c1-f1	Dlm3-c1-f1	Dlm4-c1-f1	Dlm5-c1-f1
Laboratory mixture designation	6	3	7	2	9
Cement, Lafarge I (kg/m^3)	232	226	241	229	239
Class C fly ash, Pleasant Prairie (kg/m^3)	100	97	104	99	103
Grade 120 GGBFS, Lafarge (kg/m^3)	0	0	0	0	0
Water (kg/m^3)	133	123	138	132	138
Fine aggregate, SSD (kg/m^3)	641	624	664	635	661
ASTM C 33 No. 67 coarse aggregate, 19 to 5 mm, SSD (kg/m^3)	719	707	736	711	740
ASTM C 33 No. 4 coarse aggregate, 38 to 19 mm, SSD (kg/m^3)	478	470	490	475	491
Water-reducing admixture (L/m^3)	1.31	0.73	0.17	0.32	0.16
Air-entraining admixture (L/m^3)	0.58	0.89	1.49	0.80	2.14
Water-cementitious ratio, W/Cm	0.40	0.38	0.40	0.40	0.40
Slump (mm)	65	75	65	105	25
Air content (%)	7.0	7.3	6.2	6.0	5.6
Air temperature (°C)	21	22	22	21	22
Concrete temperature (°C)	21	22	19	21	22
Density (kg/m^3)	2300	2250	2370	2280	2370

5.2 COMPRESSIVE STRENGTH

The test results for compressive strength of concrete are given in Tables 5, 6, and 7. The compressive strength of the concrete was affected significantly by the type and source of the coarse aggregate. The compressive strength of concrete made with glacial gravels from the different sources varied significantly in terms of magnitude and development pattern with time (Table 5). The compressive strength of concrete made with dolomite also varied significantly depending on the source of dolomite (Table 7).

Table 5. Compressive Strength of Concrete Made With Gravel from Difference Sources (MPa)

Mixture	7-day	14-day	28-day	90-day
Gvl1-c1-f1	24.5	26.3	33.6	41.2
Gvl2-c1-f1	19.0	20.5	26.1	31.8
Gvl3-c1-f1	20.3	24.0	28.0	34.3
Gvl4-c1-f1	23.3	27.4	30.5	35.0
Gvl5-c1-f1	19.8	22.4	24.5	30.7
Gvl6-c1-f1	19.9	25.0	28.9	37.9

Table 6. Compressive Strength of Concrete Made With Quartzite, Granite, Diabase, or Basalt (MPa)

Mixture	7-day	14-day	28-day	90-day
Qtz-c1-f1	22.5	25.2	30.1	34.7
Gnt-c1-f1	23.9	26.4	27.0	34.6
Dbs-c1-f1	26.2	31.4	38.3	40.8
Bst-c1-f1	19.1	20.8	26.9	29.5

Table 7. Compressive Strength of Concrete Made With Dolomite from Different Sources (MPa)

Mixture	7-day	14-day	28-day	90-day
Dlm1-c1-f1	28.3	32.9	36.4	41.4
Dlm2-c1-f1	21.7	24.9	29.9	35.0
Dlm3-c1-f1	25.0	30.1	35.3	40.7
Dlm4-c1-f1	20.0	23.5	27.2	31.9
Dlm5-c1-f1	25.5	32.4	36.1	40.3

5.3 COEFFICIENT OF THERMAL EXPANSION

The test results for coefficient of thermal expansion (CTE) of concrete are given in Tables 8, 9, and 10. Among the types of coarse aggregate tested, the concrete made with quartzite (Qtz-c1-f1) had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F) (Table 8). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F). This implies that the sources of glacial gravel selected for this project had different rock and mineral compositions, which affected the CTE. The CTE of concrete mixtures made with dolomite from the five sources was relatively uniform, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F) (Table 10).

The mechanistic-empirical design guide provides ranges of CTE values of aggregates for use in estimating CTE of concrete for Level 2 design [ARA 2004]. However, these ranges are quite wide, for example CTE of 7.0 to 9.9 × 10^{-6}/°C (3.9 to 5.5 × 10^{-6}/°F) for dolomite aggregate. For the most accurate design, the CTE of concrete should be determined by actual testing.

Table 8. Coefficient of Thermal Expansion (CTE) of Concrete Made With Gravel from Different Sources (microstrain/°C)

Mixture	28-day CTE (microstrain/°C)
Gvl1-c1-f1	10.4
Gvl2-c1-f1	10.5
Gvl3-c1-f1	10.7
Gvl4-c1-f1	9.9
Gvl5-c1-f1	9.7
Gvl6-c1-f1	10.1

Table 9. Coefficient of Thermal Expansion (CTE) of Concrete Made With Quartzite, Granite, Diabase, or Basalt (microstrain/°C)

Mixture	28-day CTE (microstrain/°C)
Qtz-c1-f1	12.2
Gnt-c1-f1	9.5
Dbs-c1-f1	9.3
Bst-c1-f1	9.3

Table 10. Coefficient of Thermal Expansion (CTE) of Concrete Made With Dolomite from Different Sources (microstrain/°C)

Mixture	28-day CTE (microstrain/°C)
Dlm1-c1-f1	10.6
Dlm2-c1-f1	10.5
Dlm3-c1-f1	10.4
Dlm4-c1-f1	10.6
Dlm5-c1-f1	10.8

6. SUMMARY

Concrete mixtures were made using different types coarse aggregates obtained from various sources in Wisconsin, USA. Based on the test results obtained, the following summary is presented.

The compressive strength of the concrete was affected significantly by the type and source of the coarse aggregate.

Among the types of coarse aggregates tested, the concrete made with quartzite (Qtz-c1-f1) had the highest CTE, 12.2 microstrain/°C (6.8 microstrain/°F). The concrete mixtures made with diabase, basalt, and granite showed the lowest CTE, ranging from 9.3 to 9.5 microstrain/°C (5.2 to 5.3 microstrain/°F). The CTE of concrete made with glacial gravel from the six sources ranged from 9.7 to 10.7 microstrain/°C (5.4 to 5.9 microstrain/°F).

The CTE of concrete mixtures made with dolomite from the five sources was relatively uniform, ranging from 10.4 to 10.8 microstrain/°C (5.8 to 6.0 microstrain/°F). The types and sources of cementitious materials had a negligible influence on the CTE of concrete made with dolomite.

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