Freeze-Thaw Studies on Concrete Structural Elements

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The effect of freeze-thaw cycles on plain concrete decks and concrete-filled steel grid decks is presented. The test program stimulates field temperature conditions. An attempt has been made to correlate the freeze-thaw effect to the longitudinal growth behavior of concrete-filled steel grid decking systems. To study the longitudinal growth, emphasis has been placed on the determination of expansion and contraction coefficients of concrete for different temperature ranges. Residual tensile strain buildup, a result of the differential expansion and contraction coefficient of concrete, is found to be a function of freeze-thaw cycles. Thermal incompatibility between concrete and steel and the consequent growth in concrete-filled steel grid decks are dealt with from the viewpoint of thermal creep.

Concrete is an important construction material that has many advantages and few limitations. One of the major concerns is the response and durability of concrete under environmental conditions such as thermal cycling. In most of the applications, concrete is used along with steel, resulting in composite members of reinforced or prestressed concrete components. In such components, concrete and steel are forced to deform together under temperature fluctuations. However, the difference in thermal properties of concrete and steel results in thermal strain incompatibility and eventually leads to residual stress buildup (*1*). The residual stress buildup is tensile in nature and becomes cumulative with the number of freezing and thawing cycles. The strains due to freezing in the case of saturated cement paste specimens were reported (*2*) to be as high as 1600 microstrains, and about 500 microstrains of permanent elongation after reaching the original temperature was also reported. Pigeon et al. determined the freeze-thaw durability of concrete and found a strain buildup of 2,000 to 5,000 microstrains over 100 cycles for varying constituents in concrete (*3*). Attiogbe et al. determined the freeze-thaw durability of concrete containing superplasticizers and reported a strain buildup on the order of 1,300 microstrains over 300 cycles (*4*). The difference between thermal coefficients of expansion and contraction, which is one of the causes for residual stress buildup, has been reported by many researchers (*5–7*). The variation in coefficients is more pronounced above and below the freezing point of water. The moisture content in the pores of concrete freezes and forms ice below 0°C (32°F). The materials in concrete contract but ice in pores expands below 0°C (32°F), resulting in a decreased coefficient of expansion of concrete. The coefficient of expansion and contraction above and below the freezing point of water, for a concrete with a 0.49 water-to-cement ratio that has been dry-cured for 28 days, has been reported to be 4.26 $\times$ 10^{-6} and 2.83 $\times$ 10^{-6}, respectively (*5*).

The limitations of this phenomenon are cracking and growth of concrete, which are generally associated with regions that experience a number of freeze and thaw cycles during winter seasons. Cracks permit water to enter into concrete. The moisture ingress leads to enlargement of the cracks due to freezing, which in turn permits additional water to seep and cause concrete deterioration.

Longitudinal growth, which poses a very serious maintenance problem, is found extensively in concrete-filled steel grid decks (*8–10*). For instance, an 11-span highway bridge 217 m (710 ft) long, built in 1948 at Massillon, Ohio, that had a concrete-filled steel grid decking system was closed to traffic in December 1964 because of growth in the bridge deck (*8*). The deck growth caused the sidewalks to crack and buckle and the expansion joints to close. The deck growth resulted in failure of welds between the deck and supporting stringers and dislocation of the deck from its abutment. Sturrett (*11*) reported a growth in concrete-filled decks on the order of 102 mm (4 in) for 31 m (100 ft) of length in the field. He also reported that the maximum force in one cross bar of the concrete-filled steel grid deck can be as high as 58 kN (13 kips). Additional literature (*9*) reveals that more than half of the totally bare (without concrete overlay) concrete-filled steel grid decks and more than a quarter of concrete-filled steel grid decks with concrete overlay showed a deck growth problem in Ohio alone.

The probable reasons attributed to the deck growth were corrosion of steel and use of expansive aggregates (*8*). Some researchers (*9,10*) also put forth remedial measures for the concrete-filled deck growth problem. However, the design details accounting for the effect of thermal fluctuations, thermal movements, freeze and thaw cycles, thermal incompatibilities, and separation of concrete from steel, which can be attributed to differential expansion between concrete and steel, were not given much importance. Yanev (*12*) and Callahan et al. (*13*) have pointed out the importance of such parameters in their work.

The objective of this paper is to present (a) expansion and contraction phenomena of concrete at different temperature ranges; (b) expansion and contraction coefficients, and residual stress buildup within concrete due to freeze-thaw cycling, for plain concrete slabs and concrete-filled steel grid decks; (c) thermal incompatibility between concrete and steel in concrete-filled steel grid decks leading to their growth; and

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(d) concrete strength (tensile and compressive) variations before and after freeze-thaw cycles.

SCOPE

Accelerated tests were conducted in a laboratory environment on plain concrete slabs and concrete-filled steel grid decks, simulating field conditions to study the deck growth phenomenon. The test program was designed on the basis of simulating field temperature and freeze-thaw effects only. Test specimens were monitored for dry and wet conditions, and humidity conditions were maintained at the ambient levels only. The length and width of the deck specimens were scaled to suit the apparatus size; however, the specimen thickness was nearly identical to the field conditions. The temperature in the core of the concrete slab and concrete-filled grid decks was monitored with the help of embedded thermocouples. Strain data were obtained using strain gauges.

The test specimens consisted of plain concrete slabs and concrete-filled steel grid decks. Table 1 summarizes the specimen sizes and main bar and cross bar spacing and orientation in addition to other information such as temperature range, duration of each cycle, and number of cycles for each specimen tested for freeze-thaw effect. Figure 1 shows the main bar and cross bar sizes used in the concrete-filled steel grid deck specimens. Eight specimens were studied. Series I consisted of a concrete-filled steel grid deck and an open steel grid deck. The concrete-filled steel grid deck was cast in the laboratory. The specimens of Series I were subjected to 18 cycles in the temperature procession of 21 to −32 to 21°C (70 to −25 to 70°F). Series II and III comprised two concrete-filled steel grid decks and a plain concrete slab. All the specimens in Series II and III were cast in the laboratory. The temperature procession for specimens in Series II and III was 21 to 2 to −17 to 2 to 21°C (70 to 35 to 0 to 35 to 70°F). Series II and III specimens were subjected to 70 and 155 cycles, respectively. Series III specimens were subjected to both dry and wet cycles. The duration of each cycle for all the specimens in Series I through III was 24 hr. The mix proportions of specimens within the series was kept constant.

EQUIPMENT AND MEASURING DEVICES

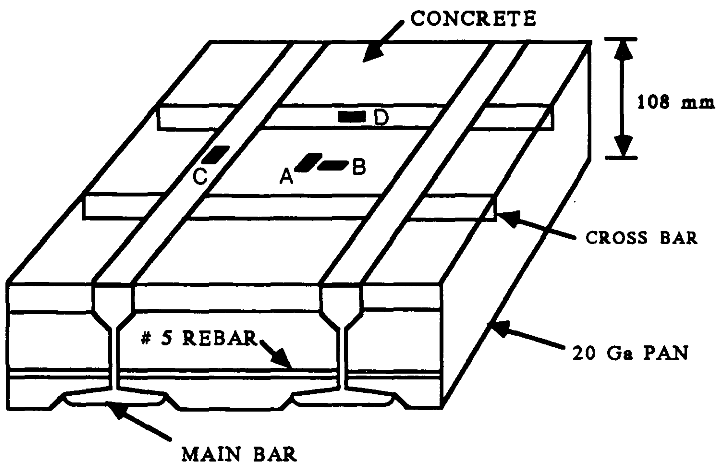
The equipment and measuring devices used for the testing program were Tenny Environmental Equipment (chamber), Omega Thermocouple Thermometer, Datran II Multichannel Strain Indicator, thermocouples, and strain gauges.

The Tenny Environmental Equipment was designed to create and control the temperature and relative humidity within the specified operating ranges. Simulated environments were controlled automatically by manual selection switches. The clear working space available inside the chamber was 1.2 × 1.2 × 1.2 m (48 × 48 × 48 in.). The chamber had a full opening door, viewing window, and electrical and thermocouple feed throughs. The temperature variations were achieved using a cam device. The Omega Thermocouple Thermometer, which was used to monitor the temperature in the core of the specimens, was a digital panel meter and served as a readout for J-, K-, T-, or E-type thermocouple sensors. The J-type thermocouple was used throughout the experimental program. The Datran II strain indicator, with a scanner control section and 80 channels used to measure strains in concrete and steel, was a precision DC millivolt-per-volt instrument that had a high degree of operational versatility and reliability. The types of strain gauges used were EA-06-250BG-120 for steel and EA-06-20CBW-120 for concrete. The strain gauges

TABLE 1 Type, Size, and Freeze-Thaw Parameters of Specimens

SPECIMEN TYPE	SERIES #	SPECIMEN SIZE (mm)	MAIN BAR DIRECTION	TEMPERATURE RANGE (°C)	NO. OF CYCLES
1. FILLED DECK	I	254x914x127	LONG	21 To -32 To 21	18
2. OPEN STEEL GRID		254x914x127	LONG	21 to -32 To 21	18
1. FILLED DECK	II	305x914x108	LONG	21 To 2 To -17 To 2 To 21	70
2. FILLED DECK		406x1219x108	SHORT	21 To 2 To -17 To 2 To 21	70
3. PLAIN CONC. DECK		305x914x108	-	21 To 2 To -17 To 2 To 21	70
1. FILLED DECK	III	305x914x108	LONG	21 To 2 To -17 To 2 To 21	155**
2. FILLED DECK		610x610x108	LONG	21 To 2 To -17 To 2 To 21	155**
3. PLAIN CONC. DECK		305x914x108	-	21 To 2 To -17 To 2 To 21	155**

Note: 1 in = 25.4 mm ; (°F - 32)/1.8 = °C
****Wet type of cycles are conducted beyond 105 cycles**
Main bar spacing is 203 mm in all the specimens
Cross bar spacing is 102 mm in all the specimens
Duration of each cycle is 24 hours in all the specimens



MAIN BAR SIZE AND SPACING: 108mm I SECTION OF 5# @ 203 mm C/C
CROSS BAR SIZE AND SPACING: 38mmx6mm @ 203 mm C/C
A : STRAIN GAGE ON MAIN BAR STEEL (MB)
B : STRAIN GAGE ON CROSS BAR STEEL (CB)
C : STRAIN GAGE ON CONCRETE IN MAIN BAR DIRECTION (MBD)
D : STRAIN GAGE ON CONCRETE IN CROSS BAR DIRECTION (CBD)

FIGURE 1 Strain gauge location and nomenclature in concrete-filled steel grid decks.

were self-temperature-compensating, hence the readings were free from temperature-induced strain. A three-wire lead system was used to eliminate the length effect of lead wires. A 330-DFV type of conductor cable (lead wire) was used.

STRAIN GAUGE POSITIONS AND PLACING OF SPECIMENS

Strain gauges were placed on the main bar steel (MB in figures and tables), on the cross bar steel (CB in figures and tables), and on the concrete, one in the main bar direction (MBD in figures and tables) and one in the cross bar direction (CBD in figures and tables) as shown in Figure 1. This strain gauge pattern was used at the center cells and at the end cells. Since the end cells were free to expand (no restraint from adjacent cells), the strain gauge readings were obviously greater in the end cells than in the center cells and did not represent the actual expansion or contraction values. Therefore, only the readings given by the strain gauges fixed in the center cells were used for the synthesis of experimental data. In the plain concrete slab specimens, strain gauges were fixed in the long and short directions at the center of the specimen. All the specimens of Series I and III were placed flat resting on rollers and supported on wooden blocks. The specimens of Series II were made to rest on their edges in the longer direction by placing them on two wooden blocks at the ends. The arrangement ensured minimum restraint to expansion and contraction in the specimens. Care was taken not to disturb the original position of the specimens until the required number of freeze-thaw cycles was completed.

The experimental procedure mainly involved the measurement of strains during the progress of each cycle. The strain readings were read at regular intervals. The cam, designed according to the required temperature range and duration of each cycle, provided the simulated field conditions. The thermocouple readings, indicating the temperature inside the deck specimens, were read at regular intervals. The temperature readings from the thermocouple and cam indicator were found to be nearly identical at any given time.

EXPERIMENTAL DATA

The experimental data in terms of strain readings were used to

1. Establish the residual strain buildup per cycle and cumulative residual strains in the plain concrete slabs in both long and short directions, main and cross bar steel, and concrete in the main and cross bar directions (for concrete-filled decks). The residual strain was calculated as an increase or decrease in the strain reading from the previous reading at a given time.
2. Compute the coefficients of thermal expansion and contraction in concrete in all the specimens. This was computed by taking the average increase or decrease in strains per degree increase or decrease in the temperature for a given range of temperature.
3. Compute the forces developed because of residual strains in steel and concrete for concrete-filled steel grid decks. The residual strain buildup over a number of cycles was computed.

Forces were then calculated using these residual strains by a simple stress-strain relationship. More details can be found elsewhere (*1*).

To determine tensile and compressive strengths of concrete, split tension and axial compression tests were conducted on concrete cylinders before and after freeze-thaw cycles. The data from these tests were used to determine the change in the strengths.

RESULTS

Figure 2 indicates the residual strain buildup in concrete and steel for Series I concrete-filled steel grid decks. The initial discrepancy in the strain readings as seen in Figure 2 can be attributed to the initial adjustment that the specimen undergoes for shrinking cracks when subjected to freeze-thaw cycles. Figure 2 indicates that the open steel grid deck is unaffected by the freeze-thaw cycles. However, it can be seen from Figure 2 that there is residual strain buildup in steel for concrete-filled steel grid decks. Figure 3 is a plot showing residual strains versus number of cycles for a Series II plain concrete deck. Figures 4 and 5 show the residual strain plots versus number of freeze-thaw cycles for two concrete-filled steel grid decks of Series II. Because the strain gauge malfunctioned on concrete in the main bar direction of the Series II decks and on cross bar and main bar steel in Series III decks, readings were not available beyond 32 and 105 cycles, respectively, as seen in Figures 4 and 6. From Figure 5, it can be seen that strains in the main bar have stabilized, whereas strains in the cross bar follow an increasing trend. Figures 6 through 8 show the residual strain plots versus number of freeze-thaw cycles for Series III plain concrete deck and two Series III concrete-filled steel grid deck specimens. The residual strain plots up to 105 cycles are due to dry cycles, and the residual strain plots from 106 cycles up to 155 cycles are due to wet cycles. A trend similar to that in Series II specimens can be seen in Series III specimens with regard to the residual strain buildup in the main and cross bars. Figures 6 through 8 also indicate the effect of moisture on the residual strain buildup.

Tables 2 and 3 give the in-plane force calculations due to residual strain buildup in concrete and steel for concrete-filled steel grid decks of Series I, II, and III. The average coefficients of expansion and contraction for concrete in the concrete-filled steel grid decks and plain concrete deck of Series I and II are shown in Table 4. Similar results for plain concrete slabs of Series II and III are also shown in Table 4.

OBSERVATIONS AND DEDUCTIONS

The following salient features are brought out after synthesizing the experimental data and also from visual examination of the filled deck specimens that were tested in the Major Units Laboratory at West Virginia University:

- Microcracks were observed that were due to concrete shrinkage along the main bar as well as the cross bar directions of concrete-filled decks. The cracks were less severe along the cross bars because of the continuity of concrete beneath the cross bars.
- The initial strain buildup from thermal cycling was large up to a strain level required to overcome shrinkage strains in concrete-filled decks. This was referred to as "*shrinkage compensation*."
- The initial residual strain buildup in concrete due to thermal creep for 30 to 40 cycles was equivalent to 800 to 1,000 microstrains. This initial concrete strain buildup was attributed to the concrete shrinkage compensation (which was checked by monitoring plastic as well as drying shrinkage after actual pouring of concrete into the steel grid). The thermal strain buildup over the initial 800 to 1,000 microstrains caused by shrinkage strains was found to be 300 to 400 microstrains. Such a magnitude of buildup has also been observed by other researchers (*2–4*).
- Thermal strains in concrete and steel (cross bar) were found to be tensile and increasing with the number of freeze-thaw cycles.

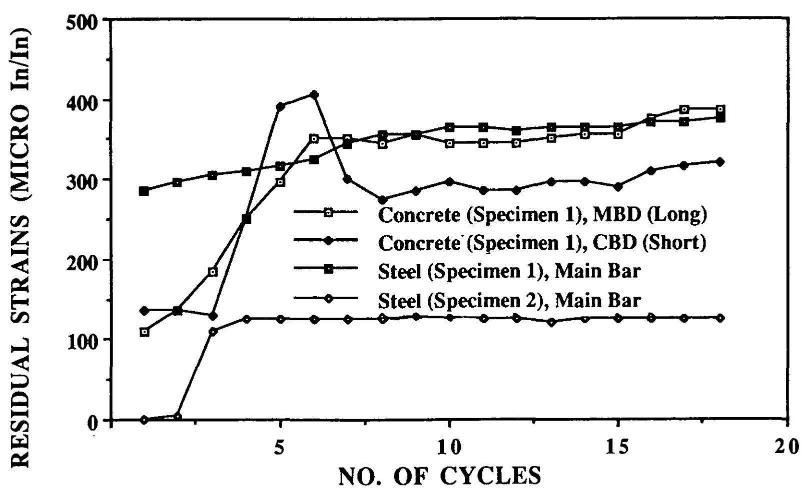


FIGURE 2 Residual strains versus number of cycles: Series I, Specimens 1 and 2 (254 × 914 × 127 mm).

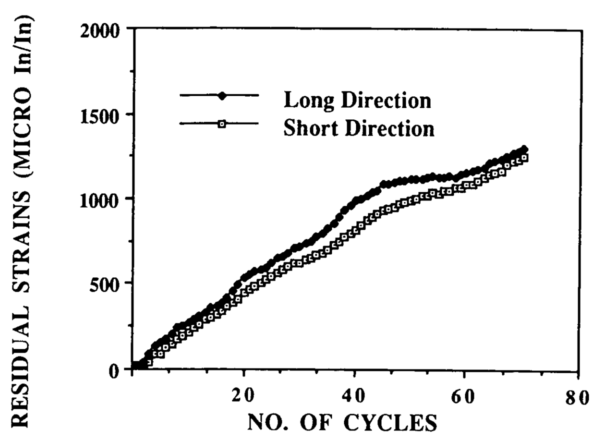


FIGURE 3 Residual strains versus number of cycles: Series II, Specimen 3 (305 × 914 × 108 mm).

- Main bar strains tend to stabilize after about 25 freeze-thaw cycles. The concrete and cross bar strains did not stabilize at the same number of cycles, but continued to increase. The earlier stabilization in the main bar was attributed by the authors to relatively higher stiffness and lower thermal creep in that direction.
- Residual strains in terms of their magnitude in steel and concrete were not same in the same direction (e.g., Figures 4 and 5). This difference led to strain incompatibility between steel and concrete in the filled grid deck and needs to be properly accounted for in the design.
- Concrete was found to be more susceptible than steel in terms of residual strain buildup because of its heterogeneity and anisotropy.
- In laboratory experiments, concrete-filled steel grid decks have been found to develop residual stresses under freeze-thaw cycles. However, such a buildup is not found in open steel grid decks (Figure 2).

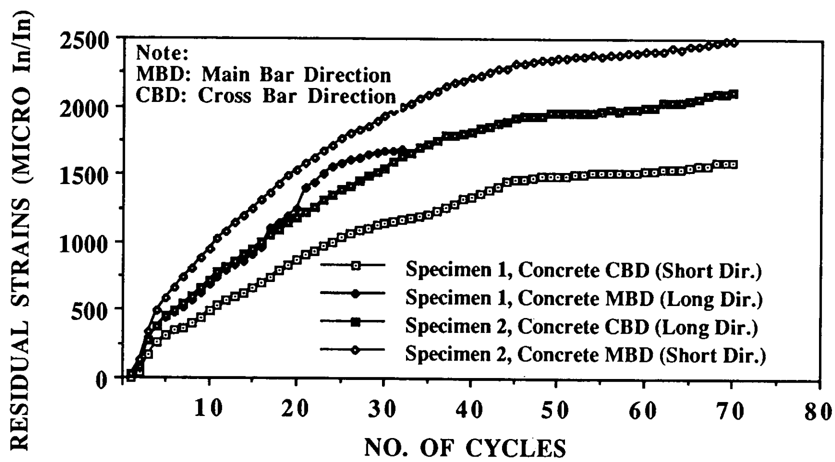


FIGURE 4 Residual strains versus number of cycles: Series II, Specimen 1 (305 × 914 × 108 mm) and Specimen 2 (406 × 1219 × 108 mm).

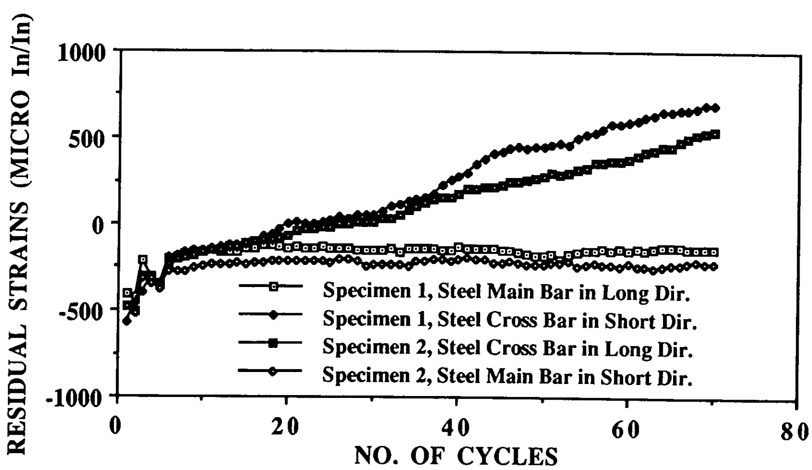


FIGURE 5 Residual strains versus number of cycles: Series II, Specimen 1 (305 × 914 × 108 mm) and Specimen 2 (406 × 1219 × 108 mm).

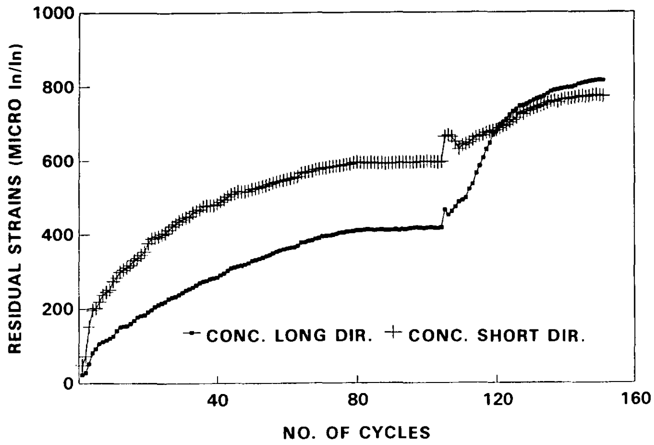


FIGURE 6 Residual strains versus number of cycles: Series III, Specimen 1 (305 × 914 × 108 mm) and Specimen 2 (610 × 610 × 108 mm).

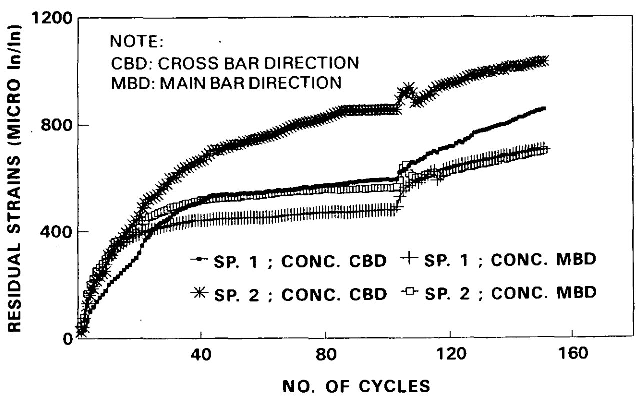


FIGURE 7 Residual strains versus number of cycles: Series III, Specimen 3 (305 × 914 × 108 mm).

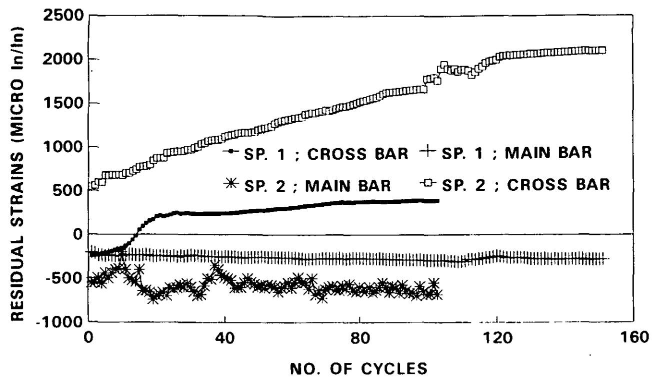


FIGURE 8 Residual strains versus number of cycles: Series III, Specimen 1 (305 × 914 × 108 mm) and Specimen 2 (610 × 610 × 108 mm).

- From Table 4, the coefficients of expansion and contraction of concrete in the filled deck specimens are 2.91×10^{-6} and 2.08×10^{-6} [Series II, Specimen 1, Gauge B, −17 to 2°C (0 to 35°F) temperature rise, and 2 to −17°C (35 to 0°F) temperature fall]. The expansion and contraction coefficients of concrete in the filled decks are lower than the values of the coefficients of expansion and contraction of concrete (3.95×10^{-6} and 3.47×10^{-6}, Series III, Specimen 3, Gauge B) in the plain concrete decks. Such low values in the filled decks have resulted from the presence of steel in filled decks.
- From Tables 2 and 3, the forces developed in concrete and steel due to residual strain buildup were found to be different, which revealed strain incompatibility.
- The tensile strength of concrete was reduced by the effect of freeze-thaw cycles. The maximum decrease in tensile strength was about 30 percent. A very small increase in the compressive strength was observed. Pigeon and Lachance (*14*) also reported a small increase in the compressive strengths of specimens that were subjected to freeze-thaw cycles.

TABLE 2 Force Due to Residual Strains in Steel Main Bar and Concrete (Main Bar Direction)

SERIES #	SPECIMEN #	RESIDUAL STRAINS (10^{-6})			FORCE (N)			TOTAL FORCE (N)	
		MB	PAN	CONC. (MBD)	MB	PAN	CONC. (MBD)	STEEL	CONC. (MBD)
I	1	30	-	40	6.6	-	21.4	6.6	21.4
II	1	78	78	46	15.3	3.0	19.7	18.3	19.7
	2	58	58	76	11.4	2.2	32.5	13.6	32.5
III	1	15	15	10	2.9	0.6	4.3	3.5	4.3
	2	34	34	22	6.7	1.4	9.4	8.1	9.4

Note: 1 lbf = 4.45 N; -: No bottom pan
The residual strains in the pan are assumed to be equal to the residual strains in the main bar

TABLE 3 Force Due to Residual Strains in Steel Cross Bar and Concrete (Cross Bar Direction)

SERIES #	SP. #	RESIDUAL STRAINS (10^{-6})				FORCE (N)				TOTAL FORCE (N)	
		CB	PAN	REBAR	CONC. (CBD)	CB	PAN	REBAR	CONC. (CBD)	STEEL	CONC. (CBD)
I	1	50	50	50	25	2.5	1.0	2.1	6.7	5.6	6.7
II	1	146	146	146	121	3.4	0.5	6.0	32.3	9.9	32.3
	2	165	165	165	197	3.9	3.2	6.8	42.1	13.1	42.1
III	1	68	68	68	40	1.6	1.3	2.8	8.5	5.7	8.5
	2	228	228	228	88	5.3	4.4	9.4	18.8	19.1	18.8

Note : 1 lbf = 4.45 N
The residual strains in the pan and the rebar are assumed to be equal to the residual strains in the cross bar

• The high strains observed in concrete are not unusual. There are reports (*2*) that the strains due to freezing in saturated cement paste specimens can be as high as 1,600 microstrains; on thawing to original temperature, about 500 microstrains of permanent elongation has been observed. However, this is encountered where moisture in the specimen is involved in the freeze-thaw cycles.

• From Figures 6 through 8, the residual strain buildup due to water can be noted. A sudden increase in residual strains with the addition of water is noted. Thus, the effect of moisture is severe on residual strain buildup.

CONCLUSIONS

On the basis of our limited experimental results and theoretical analysis, the preliminary conclusions follow.

The thermal coefficients of concrete varied for different temperature ranges. The thermal coefficients of expansion and contraction within the concrete itself were different. Residual tensile strain buildup was observed in concrete and cross bar steel of concrete-filled steel grid decks. However, a significant residual strain buildup was not noted in the main bar steel owing to its relatively higher stiffness. Residual ten-

TABLE 4 Coefficient of Expansion and Contraction as Determined on Concrete in Concrete-Filled Steel Grid Decks and Plain Concrete Decks

SERIES/ SPECIMEN #	INCREASING TEMP. RANGE	COEFF. OF EXPANSION (10^{-6})		DECREASING TEMP. RANGE	COEFF. OF CONTRACTION (10^{-6})	
		GAGE A	GAGE B		GAGE A	GAGE B
I - 1	-32 TO 21	2.10	1.91	21 TO -32	1.64	1.84
II - 1	-17 TO 2	1.99	2.91	2 TO -17	1.11	2.08
	2 TO 21	1.98	2.39	21 TO 2	1.47	2.74
II - 2	-17 TO 2	1.87	2.62	2 TO -17	1.67	2.12
	2 TO 21	2.18	2.94	21 TO 2	2.19	2.52
II - 3	-17 TO 2	5.10	4.54	2 TO -17	3.81	3.81
	2 TO 21	4.35	4.01	21 TO 2	3.13	2.98
III - 3	-17 TO 2	4.65	3.95	2 TO -17	3.14	3.47
	2 TO 21	4.08	3.73	21 TO 2	3.97	3.33

Note : All temperatures in ^{o}C
(^{o}F - 32)/1.8 = ^{o}C

sile strains in steel and concrete of a filled grid deck were different in the same direction, which revealed strain incompatibility. The behavior under thermal loads of concrete in combination with steel was different from the behavior of concrete alone in terms of the magnitudes of the expansion and contraction coefficients. Freeze-thaw cyclic effect led to decreased tensile strength of about 30 percent and very little increased compressive strength properties of concrete.

In the present work, the effects of different moisture conditions and humidity levels were considered in a limited manner. To establish proper understanding of freeze-thaw effects in concrete, extensive amounts of experimental data generation and interpretation must be accomplished from the viewpoint of microscopic material behavior. Emphasis was given to thermal expansion and contraction coefficients of concrete. However, other thermal properties such as thermal conductivity, thermal diffusivity, and specific heat, must be investigated. In the present work, there was no special control placed on the concrete mix parameters such as water-cement ratio, mix proportions, type of aggregates, curing techniques, and age. Hence, these must be accounted for in future research. Detailed investigations must be carried out to establish the effect of freeze-thaw cycles on concrete strength properties and strain incompatibility aspects between steel and concrete. Besides filled decking systems, other systems, such as reinforced concrete decks, should be investigated. Finally, the real challenge for future research is to develop concrete admixtures that can minimize, if not eliminate, the freeze-thaw effects on concrete while properly accounting for the behavior of admixtures in the concrete mix.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support given to this research study by the West Virginia Department of Highways, and FHWA. The authors would also like to acknowledge Udaya B. Halabe and Anne Wilkinson for proof reading and reviewing this paper.

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Publication of this paper sponsored by Committee on General Structures.