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GREEN SIDEWALKS USING SUSTAINABLE TWO-STAGE CONCRETE

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ABSTRACT

Two-stage concrete (TSC) is a special type of concrete, which has a high potential for use in sidewalk construction owing to its high volume stability. TSC is characterized by its high coarse aggregate content. Hence, using recycled solid waste materials as a coarse aggregate will increase TSC sustainability, while providing a cost-effective alternative to natural aggregates. Aggregates are pre-placed in TSC. Hence, water absorption by recycled concrete aggregates and the associated rheology problems do not exist in TSC. This study explores the performance of green TSC sidewalks incorporating recycled concrete aggregates (RCA) and crumb rubber from scrap tires. Mechanical properties of the proposed green TSC including compressive strength, modulus of elasticity, flexural strength and toughness, as well as durability to freeze-thaw cycles were investigated. Results show a slight reduction in TSC mechanical properties due to the use of RCA. Moreover, incorporating tire particles reduced TSC mechanical properties significantly, while improving its toughness and freeze-thaw resistance. Addition of recycled tire steel wires allowed to overcome the negative effects on the mechanical properties induced by crumb tire rubber. Therefore, recycling solid waste materials in TSC sidewalks can be an effective strategy to beneficiate such waste materials.

Keywords: Green two stage; concrete, recycled aggregates, recycled tire rubber, recycled tire steel wires.

1. INTRODUCTION

Solid wastes including construction and demolition materials, paints and waste tires are a major concern from an environmental perspective. These wastes are often deposited in landfills. It has been estimated that about 175 million tons of construction and demolition wastes are generated per year in North America (U.S.EPA 2009; Yeheyis et al. 2013). In addition, waste tires pose significant health and environmental concerns. It was reported that about 330 million tons of waste tires are generated in North America (Kim et al. 2011). Therefore, it is highly encouraged to reuse these wastes in other applications.

According to the Canadian Infrastructure Report Card (2016), 28% of the total sidewalks in Canada are in need of replacement. It was reported that premature failure can occur after five years of concrete sidewalks construction due to severe winter weather (Zhan 1997). As reported by Roads Construction Standard Specifications (2015), concrete sidewalks shall comply with the CSA A23.1 requirements for class C2 exposure (i.e. non-structurally reinforced concrete exposed to chlorides with or without freeze-thaw conditions).

Rubberized concrete can be a suitable solution to produce sustainable sidewalks where strength is not of an utmost priority. In conventional concrete, the addition of rubber particles as partial replacement for coarse aggregates can improve its service life. Previous study by Siddique and Naik (2004) found that the freeze-thaw resistance of concrete was improved with addition of rubber particles. This is attributed to the fact that concrete incorporating rubber particles contains an air-void system within the concrete matrix, resulting in better freeze-thaw resistance (Siddique and Naik 2004). Rubber particles are considered as a high-strain capacity material, hence, it can increase concrete ductility (Topçu 1995). Moreover, rubber particles can act as crack arresters to control the initiation and propagation of cracks (Turatsinze et al. 2005). Nevertheless, the compressive strength and workability of conventional concrete are negatively affected by adding rubber particles, especially at higher replacement rates (Taha et al. 2008).

Two-Stage Concrete (TSC) is a special type of concrete produced by placing coarse aggregate particles in the formwork, followed by grout injection (Najjar et al. 2014). Hence, this concrete production technique can accommodate the workability problems induced by recycled concrete aggregates due to their higher water absorption capacity. Moreover, TSC has 50% more coarse aggregate content than that of conventional concrete (Abdelgater 1996). Thus, TSC made with recycled materials as partial replacement for coarse aggregates can be a more sustainable alternative for utilization of waste materials. This paper explores the possibility of using the TSC technology to produce green sidewalks. The effects of incorporating recycled concrete aggregates and tire rubber wastes on the mechanical performance and freeze-thaw resistance of green TSC are investigated. Moreover, the influence of using a sustainable grout, made with ternary binders, on TSC properties is studied.

2. EXPERIMENTAL PROGRAM

2.1 Materials and Grout Mixture Proportions

For grout mixtures, CSA A3001 GU cement (noted herein OPC) was used as the main binder. Two types of supplementary cementitious materials (SCMs) including class F fly ash (FA) and high reactivity metakaolin (MK) were added as partial replacement for OPC. Table 1 shows physical and chemical properties for the used binders. Silica sand with a fineness modulus of 1.47 and a saturated surface dry specific gravity of 2.65 was used as a fine aggregate. TSC grout mixtures with a water-to-binder ratio (w/b) of 0.45 and sand-to-binder ratio (s/b) of 1 were prepared using a single binder (i.e. grout made with 100% OPC (C)) and a ternary binder (grout made with 50% OPC, 10% MK and 40% FA (MF4)). To control the flowability of the grout mixtures, a poly-carboxylate high-range water-reducing admixture (HRWRA) with a specific gravity of 1.064 and a solid content of 34% was employed (BASF Corporation). The dosage of HRWRA for both grout mixtures was selected to comply with the requirements of ACI 304.1 (2005) (i.e. efflux time = 35-40±2 s). Table 2 presents the grout mixture proportions, which were selected based on ASTM C 938 (Standard Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete). Crushed limestone coarse aggregate with a maximum nominal size of 40 mm, a saturated surface dry specific gravity of 2.65 and water absorption of 1.63% was used in the control TSC. Recycled concrete aggregates (RCA) having size between 19-38 mm, a saturated dry specific gravity of 2.6 and water absorption of 2.0% was used to produce green TSC. Moreover, tire rubber crumbs with size of 20 mm were used as partial replacement for the recycled concrete aggregates. Recycled tire steel wires having a mean diameter of 0.2 mm, length ranging between 3 mm and 22 mm and tensile strength of 2000 MPa were incorporated in TSC. Figure 1 shows the used raw materials to produce TSC mixtures. Moreover, various TSC mixtures were prepared as shown in Table 3.

2.2 Experimental Procedures

The experimental program was conducted to study the mechanical properties as well as freeze-thaw resistance of the various TSC mixtures. TSC cylindrical specimens (150 mm × 300 mm), TSC prisms (150 mm × 150 mm × 550 mm) and TSC panels (500 mm × 500 mm × 75 mm) were prepared for each TSC mixture. The molds were first filled with coarse aggregates and then the grout was injected into the voids. Specimens were covered with wet burlap to prevent surface drying. After 24 h, specimens were demolded and cured in the moist room (T = 25°C and RH = 98%) until the testing age (i.e. 28 days).

The compressive strength and the static modulus of elasticity of TSC were evaluated according to ASTM 943 (Standard Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Pre-placed-Aggregate Concrete in the Laboratory) and ASTM C469/C469M (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression), respectively. Moreover, the flexural performance and toughness of TSC prisms were determined using a three-point bending test based on ASTM C1609/C1609M-10 (Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete-Using Beam with Third-Point Loading). The test was conducted using a closed loop deflection-controlled testing with a loading rate of 0.1 mm/min.

The freeze-thaw resistance was assessed based on ASTM C666-2015 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing). TSC prisms (275 mm × 75 mm × 75 mm), obtained by cutting TSC panels, were used to evaluate the freeze-thaw resistance of the TSC mixtures. After 28 days of curing in a moist room (temperature (T) = 25°C and relative humidity (RH) = 98%), TSC specimens were exposed to 6 freeze-thaw cycles per day. The nominal freeze-thaw cycle consisted of alternately lowering the temperature of specimens from 4 to -18°C and raising it from -18 to 4°C over a period of 4 hours. Visual inspection and mass loss of the TSC specimens were observed after 300 cycles of freeze-thaw.

Table 1: Chemical Analysis and Physical Properties of OPC, FA, and MK

	OPC	FA	MK
SiO_2 (%)	19.60	43.39	53.50
Al_2O_3 (%)	4.80	22.08	42.50
CaO (%)	61.50	15.63	0.20
Fe_2O_3 (%)	3.30	7.74	1.90
SO_3 (%)	3.50	1.72	0.05
Na_2O (%)	0.70	1.01	0.05
Loss on ignition (%)	1.90	1.17	0.50
Specific gravity	3.15	2.50	2.60
Surface area (m^2/kg)	371	280	15000

Table 2: Grout Mixture Proportions

Grout mixture ID	Grout mixture notation*	Binder (kg/m^3)			Sand (kg/m^3)	Water (kg/m^3)	HRWRA dosage (%)
		OPC	FA	MK			
C	100OPC	875	--	--	875	390	0.40
MF4	50OPC-10MK-40FA	440	350	85	875	390	0.35

*Grout mixture notation refers to the proportions of binders in the grout mixture.

Crushed limestone Recycled aggregate Tire rubber particles Recycled tire wires

Figure 1: Illustration of raw materials used to produce various TSC mixtures.

Table 3: TSC Mixtures

TSC mixture ID	Grout mixture ID*	Coarse aggregate (%)			Recycled tire wires (% by concrete volume)
		Crushed limestone (NA)	Recycled concrete aggregate (RCA)	Tire rubber crumbs (R)	
C-NA	C	100	--	--	--
C-RCA		--	100	--	--
C-R40-W0		--	60	40	--
C-R40-W1		--	60	40	1
MF4-NA	MF4	100	--	--	--
MF4-RCA		--	100	--	--
MF4-R40-W0		--	60	40	--
MF4-R40-W1		--	60	40	1

*Grout mixture proportions are presented in Table 2

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of Incorporating Recycled Concrete Aggregates and Tire Rubber Wastes

3.1.1 Compressive Strength

The compressive strength results of TSC mixtures are presented in Table 4. As expected, the compressive strength decreased as the recycled materials incorporated were added. For example, the compressive strength for the TSC mixture incorporating recycled concrete aggregates (C-RCA) was 13.7% lower than that of the control TSC mixture made with natural aggregates (C-NA). This is attributed to the rounded shape of the recycled aggregate, which affected the aggregate interlock (Abdelgader and Górski 2003). However, the used natural aggregate had a crushed shape with rough texture, which provides better surface for grout inter-keying, and consequently higher strength than that produced with the recycled concrete aggregates (Najjar et al. 2014).

Moreover, TSC incorporating 40% recycled tire rubber particles (C-R40-W0) exhibited 41% lower compressive strength than that of (C-RCA) mixture. This is ascribed to: 1) reduction of load-carrying capacity induced by the strong coarse aggregate; 2) the weaken adhesion between the rubber particles and the concrete matrix; 3) cracks can occur easily around the rubber particles due to the dissimilarity of the plastic behaviour between the rubber particles and the surrounding grout matrix (Nehdi and Khan 2001; Zheng et al. 2008; Onuaguluchi and Panesar 2014). However, the addition of 1% recycled rubber wires provided an improvement in compressive strength. For instance, the TSC mixture incorporating 40% rubber and 1% recycled wires (C-R40-W1) achieved about 30% higher compressive strength than that of the (C-R40-W0) mixture. This is due to the role of recycled wires in resisting crack formation and crack propagation in the longitudinal direction (Farnam et al 2010; Graeff et al. 2012).

Table 4: Mechanical Properties of TSC Mixtures

TSC mixture ID	Compressive strength (MPa)	Modulus of elasticity (GPa)	Flexural strength (MPa)	Toughness (J)
C-NA	30.7	38.3	3.7	0.85
C-RCA	26.5	29.8	2.8	0.55
C-R40-W0	15.6	19.0	2.2	8.82
C-R40-W1	20.3	22.6	2.8	30.52
MF4-NA	28.4	36.0	2.6	0.26
MF4-RCA	25.1	25.2	1.6	0.33
MF4-R40-W0	11.3	20.7	1.4	8.37
MF4-R40-W1	15.4	19.0	2.2	38.5

3.1.2 Modulus of Elasticity

The modulus of elasticity results of TSC mixtures incorporating recycled materials are reported in Table 4. It can be observed that TSC made with recycled concrete aggregates (C-RCA) showed around 22% reduction in modulus of elasticity compared with that of control TSC (C- NA). This is mainly attributed to the fact that recycled concrete aggregates are less stiff than natural aggregates (McNelil and Kang 2013). Incorporating recycled tire rubber crumbs in TSC significantly reduced the modulus of elasticity. For example, the (C-R40-W0) TSC mixture exhibited 36% lower modulus of elasticity than that of (C-RCA). This is ascribed to the very low elastic modulus of the added rubber particles, which affects the concrete modulus of elasticity (Turatsinze et al. 2005; Onuaguluchi and Panesar 2014). However, TSC made with the addition of 1% recycled rubber wires (C-R40-W1) achieved about 19% higher elastic modulus compared with that of (C-R40-W0). As mentioned earlier, recycled tire wires resist crack formation and arrest crack propagation, leading to improved stiffness and higher modulus of elasticity.

3.1.3 Flexural Strength and Toughness

The flexural strength results of TSC specimens incorporating waste materials are presented in Table 4. It can be observed that (C-RCA) mixture showed a reduction in flexural strength by about 24% compared with that of the (C-NA) mixture. As mentioned previously, the rounded shape of recycled concrete aggregates has an adverse effect on surface of inter-keying, leading to weaker mechanical interlock of TSC. Moreover, (C-R40-W0) exhibited flexural strength 21% less than that of the (C-RCA) mixture. On the other hand, the (C-R40-W1) mixture achieved similar flexural strength to that of (C-RCA). This is attributed to the crack bridging mechanism induced by the recycled steel wires, enhancing the flexural strength and overcoming the adverse effect of rubber particles. Interestingly, incorporating tire rubber particles and/or recycled tire wires changed the failure mode of TSC specimens from brittle (i.e. broken into two pieces) to ductile.

Figure 2 presents the load-deflection curves for different green TSC mixtures. It can be observed that (C-R40-W0) specimens exhibited sudden increase in deflection accompanied by a reduction in load capacity after the first crack. However, such specimen showed an ability to withstand post failure loads and undergo significant displacement. This is ascribed to micro-cracks reaching rubber particles, which will act as crack arresters due to their ability to sustain large elastic deformation (Toutanji 1996; and Twumasi-Boakye 2014). It was found that (C-R40-W1) achieved better improvement in the post-crack flexural behaviour than that of (C-R40-W0). This is due to the stress bridging across cracks induced by wires in this mixture, leading to enhanced post-crack flexural behaviour (Graeff et al. 2012).

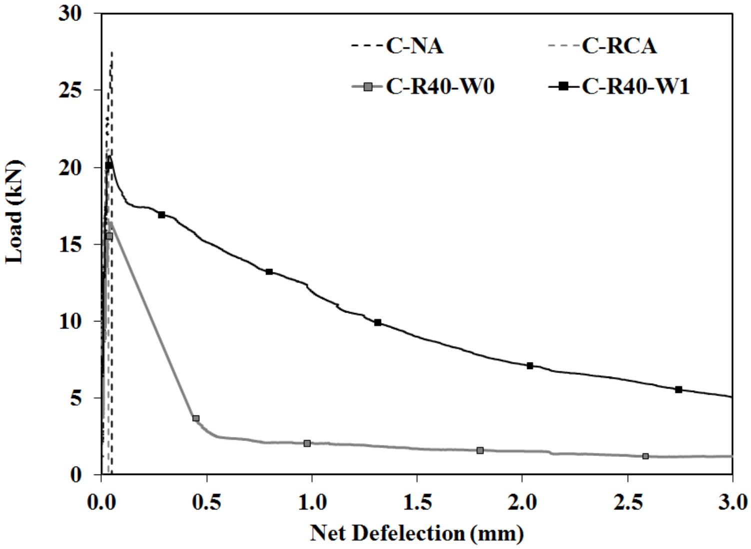

Figure 2: Load-deflection curves for TSC mixtures made with the control grout (C).

Moreover, toughness was evaluated as the area under the load-deflection curve up to 3 mm as per ASTM C1609/C1609M-10. Results showed that incorporating recycled tire rubber particles or/and recycled tire wires improved toughness. For example, (C-R40-W0) and (C-R40-W1) showed 16 and 56 times higher toughness capacity than that of the TSC made with 100% recycled concrete aggregates (C-RCA), respectively. In general, replacing coarse aggregates by tire rubber particles enhanced the concrete ability to absorb energy due to their elastic properties (Toutanji 1996). Moreover, the addition of tire wires in TSC led to increasing the required energy for crack growth (Graeff et al. 2012).

3.1.4 Freeze-Thaw Resistance

The freeze-thaw resistance of green TSC mixtures was evaluated based on visual inspection and mass loss of TSC specimens subjected to 300 freeze-thaw cycles (Figures 3 and 4). It was observed that TSC specimens made with crushed limestone (C-NA) and those made with recycled concrete aggregates (C-RCA) exhibited surface cracking and losing off concrete portions. Moreover, the mass loss of these specimens was 18% and 22%, respectively. However, (C-R40-W0) and (C-R40-W1) specimens, which are made with tire rubber crumbs, were intact along with negligible mass loss of 0.87% and 0.24%, respectively. This is attributed to the ability of tire rubber particles to induce entrained air due to their non-polar rough surface. These entrained air voids act as stress relief sites, leading to better freeze-thaw durability of concrete (Richardson et al. 2015). Furthermore, the rubber particles can relieve the stress build-up induced by ice formation by acting as mini-expansion joints inside the concrete (Kaloush et al. 2005). On the other hand, the addition of recycled tire wires can resist the development of concrete cracks induced by the action of freeze-thaw cycles (Sun et al. 1999; Graeff et al. 2012). Thus, (C- R40-W1) specimens achieved the best freeze-thaw resistance due to synergistic effects of rubber crumbs and recycled tire wires.

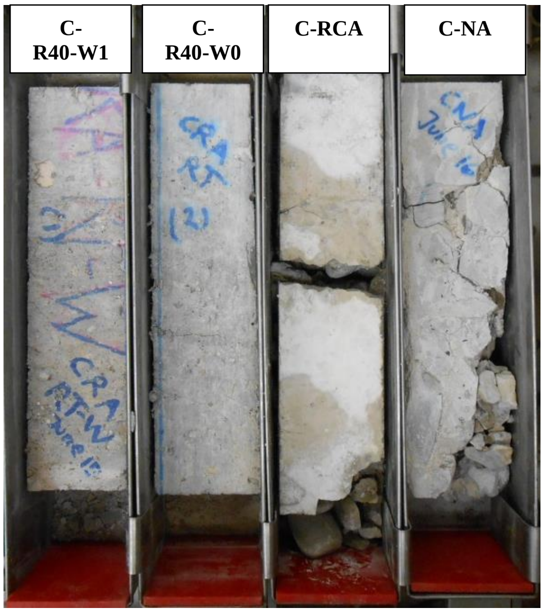

Figure 3: Illustration of various TSC specimens made with the control grout after 300 freeze-thaw cycles.

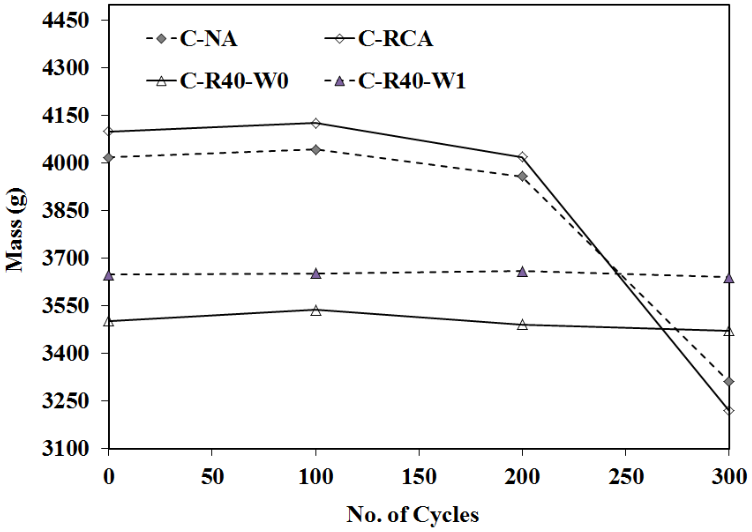

Figure 4: Mass change of TSC specimens made with the control grout versus number of freeze-thaw cycles.

3.2 Effect of Using Ternary Blended Cement

The mechanical properties of green TSC mixtures made with the MF4 grout mixture are presented in Table 4 and Figure 5. It can be observed that using the ternary binder (i.e. 50% OPC, 10% MK and 40% FA) in TSC led to a reduction in mechanical properties compared with that of the control mixture (i.e. 100 OPC). For example, the MF4-R40-W1 mixture achieved 24 %, 16% and 27% lower compressive strength, modulus of elasticity and flexural strength than that of the C-R40-W1 mixture, respectively. This is attributed to the high level of FA partial replacement for OPC in such a grout mixture (i.e. 40%). It is well known that grouts incorporating FA gain strength slowly at an age of 28 days due to the slower hydration reactions at early-age (Bouzoubaâ et al. 2004). However, incorporating 10% MK in such a grout mixture slightly offset the reduction in mechanical properties due to its high pozzolanic activity induced by MK (Najjar et al. 2016).

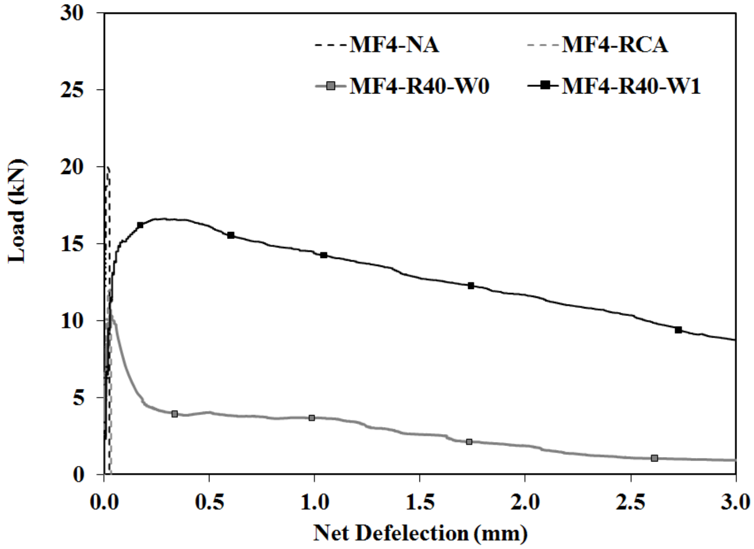

Figure 5: Load-deflection curves for TSC mixtures made with the sustainable grout (MF4).

The freeze-thaw resistance of TSC specimens made with the MF4 grout was evaluated based on visual inspection and mass loss of TSC specimens after 300 freeze-thaw cycles (Figures 6 and 7). It can be observed that the TSC specimens made with MF4 exhibited similar features of damage to that made with the control grout. However, there was a slight difference in the mass loss results, especially for those made with natural and recycled concrete aggregates. For example, the (MF4-NA) mixture exhibited 12% higher mass loss compared with that of the (C-NA) mixture. This can be attributed to the reduction in concrete strength at 28 days induced by fly ash.

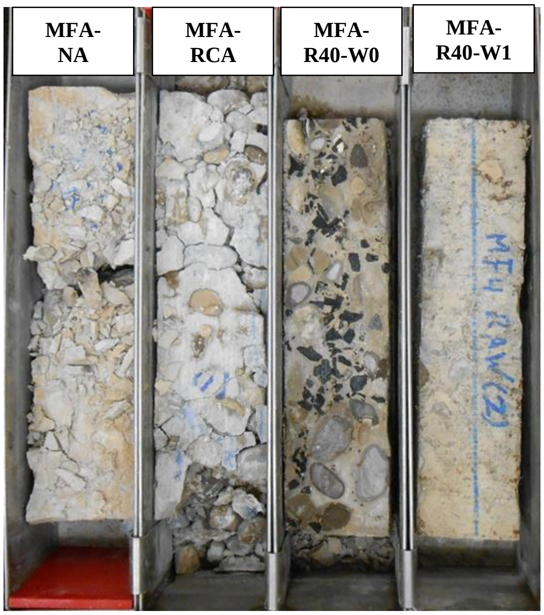

Figure 6: Illustration of various TSC specimens made with the MF4 grout after 300 freeze-thaw cycles.

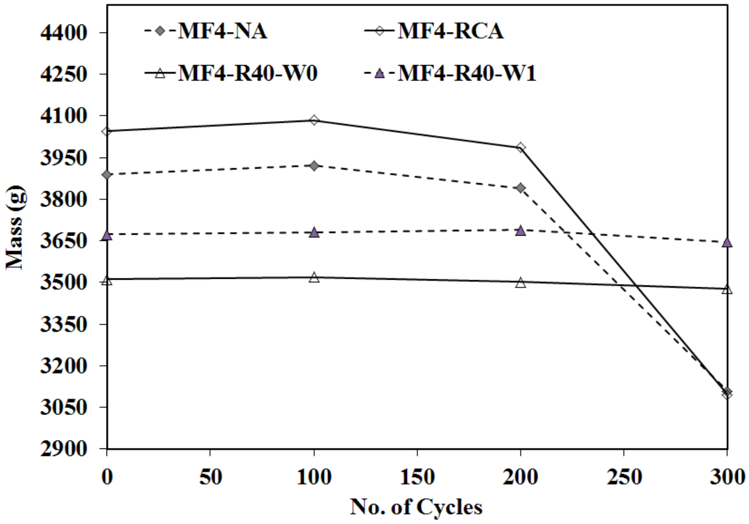

Figure 7: Mass change of TSC specimens made with the MF4 grout versus number of freeze-thaw cycles.

4. CONCLUSIONS

This study investigated the performance of green TSC mixtures intended for sidewalks construction and incorporating recycled concrete aggregates (RCA) and crumb rubber from scrap tires. Based on the results of this study, the following conclusions can be drawn:

- TSC mixtures made with recycled concrete aggregates showed a reduction in TSC mechanical properties and performed poorly under freeze-thaw cycles.
- Incorporating tire particles reduced the TSC mechanical properties significantly, while its toughness and freeze-thaw resistance were improved.
- The addition of recycled tire steel wires allowed overcoming the negative effects on the mechanical properties induced by crumb tire rubber. Moreover, the toughness and freeze-thaw resistance were significantly enhanced.
- Using fly ash and metakaolin in ternary binder for TSC resulted in a reduction in mechanical properties at 28 days, while its freeze-thaw resistance was approximately similar to that of TSC made with a single binder (control grout).
- The study showed promising results for producing green sidewalks using a new type of green TSC, which incorporates tire rubber wastes.
- There is a need for further researches to improve the strength of green TSC by addition of different cementitious material.

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