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Novel eco-efficient Two-Stage Concrete incorporating high volume recycled content for sustainable pavement construction

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HIGHLIGHTS

- TSC mixtures incorporating recycled aggregate and scrap tire rubber were developed.
- TSC incorporating high-volume recycled materials had adequate freeze-thaw resistance.
- Different percentages of scrap tire wire were used as fibre reinforcement for TSC.
- Innovative TSC technology for pavement and sidewalk construction is proposed.

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ABSTRACT

A novel eco-efficient technology for the construction of pavements and sidewalks using high recycled volume Two-Stage Concrete is proposed. Two-Stage Concrete is a special type of concrete, which is distinguished by its high coarse aggregate content and exceptional placement, whereby aggregates are first pre-placed in the mold then injected with a special grout. In this study, recycled concrete aggregate and scarp tire rubber granules were used as the preplaced material then injected by high-volume fly ash grout. Moreover, for the first time, steel wire fibers from scrap tire were used as reinforcement in Two Stage Concrete. The performance of such "green" and novel pavement construction technology in terms of mechanical properties, including compressive strength, modulus of elasticity, flexural strength and toughness, as well as durability to freezing-thawing cycles were investigated. The results demonstrate the feasibility of this eco-efficient technology to produce durable and cost-effective sidewalks and pavements, offering ease of placement and superior sustainability features.

1. Introduction

The construction of roadways and sidewalks is energy and resource-intensive, releasing large amounts of emissions and depleting natural resources. Both asphalt and concrete pavements take a tall on the environment due to depleting virgin aggregates and minerals, use of hydrocarbons, and emissions of greenhouse gas (GHG) [1]. Stripple [2] found that the energy and GHG emissions for concrete pavements in Sweden were 30% and 29% higher, respectively, than that for asphalt pavements. Conversely, the Athena Institute [3] indicated that the energy use and GHG emissions for asphalt pavements in Canada were 40% and 6.8% higher, respectively, than that of concrete pavements. Hence, there is currently clear need for sustainable pavement and sidewalk construction technology that outperforms both conventional techniques.

Beneficiating solid waste and by-products in pavement construction can enhance its environmental footprint. For instance, it has been estimated that about 4.7 million tons of waste tires need to be disposed annually in North America, causing major environmental concerns [4]. Yet such waste tires should be disposed without causing any harm to the environment [5]. Previous study [4,6] found that the resistance to freezing-thawing cycles of concrete was improved with the addition of rubber particles. This was attributed to the air-void system within the rubberized concrete matrix. Rubber particles are also considered as high-strain capacity materials, able to increase the ductility and toughness of concrete

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[7]. Moreover, rubber particles can act as crack arresters to control the initiation and propagation of cracks [8]. It was observed that replacing fine aggregate with tire rubber particles resulted in increasing the strain capacity of concrete [9]. However, the compressive strength and workability of concrete were negatively affected by the addition of rubber particles, especially at high dosages [5,10] since rubber particles can form an interlocking structure, which resists normal flow, resulting in poor workability [11]. On the other hand, a primary damage mechanism of sidewalks and pavements in North America is surface scaling and cracking induced by freezing and thawing cycles [12–14]. Hence, concrete incorporating scrap tire granules can be considered as a sustainable solution with dual benefits.

Two-Stage Concrete (TSC) is a special type of concrete produced by preplacing coarse aggregate particles in the formwork, followed by grout injection [15]. TSC has been successfully used for many years in various constructional applications [16]. TSC has 50% more coarse aggregate content than that of conventional concrete [17]. Thus, it is endowed with superior resistance against shrinkage and thermal cracking. Accordingly, when made with RCA and tire rubber granules as partial or full replacement for virgin coarse aggregates, along with scrap tire steel wire as fibre reinforcement and injected with a sustainable grout incorporating high-volume fly ash and/or other recycled by-products as binders, TSC can offer an exceptional eco-efficient alternative for the construction of economical and sustainable pavements and sidewalks. Thus, the findings of the present study can pave the way for a novel technology for the construction of more economical, sustainable and eco-efficient sidewalks and pavements with adequate mechanical strength and superior durability.

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 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 (MF)). A polycarboxylate high-range water-reducing admixture (HRWRA) with a specific gravity of 1.06 and a solid content of 34% was used to adjust the flowability of the grouts according to ACI 304.1 [18] requirements (i.e. efflux time = 35–40 ± 2 s). Table 2 presents the grout mixture proportions.

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	15,000

* 1 m^2/kg = 4.882 ft^2/lb.

RCA having particle size ranging between 19–38 mm [0.75–1.5 in.], a saturated dry specific gravity of 2.6 and a water absorption of 2.0% was used to produce the green TSC. Moreover, tire rubber particles with an average particle size of 20 mm [0.8 in.] were used as 40% partial replacement for the RCA. A maximum rubber replacement rate of 40% was used to avoid excessive reduction in concrete compressive strength. Recycled tire steel wires having a mean diameter of 0.2 mm [0.008 in.], a length ranging between 3 mm and 22 mm [0.11 in. and 0.87 in.] and a tensile strength of 2000 MPa [290 ksi] were incorporated in the green TSC. The volume fraction of the recycled tire wires was 1% in all tested mixtures. Fig. 1 exhibits the used recycled materials to produce the eco-efficient TSC mixtures. A summary of the various TSC mixtures is provided in Table 3.

2.2. Experimental procedures

Initially, aggregates were placed in the molds then injected by a grout. After casting, the specimens were covered with wet burlap to prevent surface drying. At age of 24 h, TSC specimens were demolded and cured in a moist room at temperature (T) of 25 °C [77°F] and relative humidity (RH) of 98% until testing age. Cylindrical TSC specimens (150 mm × 300 mm [6 in. × 12 in.]) were used to evaluate the compressive strength and the static modulus of elasticity for each green TSC mixture at age 28 days per ASTM C943 [19] and ASTM C469 [20], respectively. The flexural strength and toughness of TSC prisms were determined on prismatic specimens (150 mm × 150 mm × 550 mm [6 in. × 6 in. × 22 in.]) using a three-point bending test following the procedure of ASTM C1609 [21]. The resistance to freezing-thawing cycles of TSC was assessed conforming to ASTM C666 [22]. Visual inspection and mass loss for all TSC specimens were observed after 300 cycles of freezing-thawing.

3. Results and discussion

3.1. Compressive strength

The compressive strength test results of TSC mixtures are presented in Table 4. As expected, the compressive strength decreased when tire rubber particles were added. For example, the TSC specimens (CR0) incorporating 40% of recycled tire rubber particles exhibited 41% reduction in compressive strength compared to that of the control CRCA specimens (i.e. made with 100% RCA). However, the addition of 1% of recycled tire wires improved the compressive strength behaviour of TSC. For instance, TSC specimens (CR1) incorporating 40% rubber and 1% recycled tire wires achieved about 30% higher compressive strength than that of the CR0 specimens. Moreover, the TSC specimens incorporating the MF grout mixture (i.e. grout made with 50% OPC, 10% MK and 40% FA) exhibited a reduction in compressive strength compared with that of the TSC specimens incorporating the C grout mixture (i.e. grout made with 100% OPC). For example, the MFRCA specimens (i.e. made with MF grout mixture and 100% RCA) exhibited around 5% lower compressive strength than that of the CRCA specimens. Also, the MFR0 specimens (i.e. incorporating 40% recycled tire rubber particles) and the MFR1 specimens (i.e. incorporating 40% recycled tire rubber particles and 1% recycled tire wires) had about 28% and 24% reduction in compressive strength compared with that of the CR0 and CR1 specimens, respectively.

The reduction in compressive strength due to tire rubber particles addition can be ascribed to: 1) reduction of load-carrying capacity since strong coarse aggregates were partially replaced with softer granules; 2) relatively weak adhesion between rubber particles and the concrete matrix; 3) cracks that occurred around