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EXPERIMENTAL AND NUMERICAL STUDY OF TIME-DEPENDENT BEHAVIOUR OF REINFORCED SELF-COMPACTING CONCRETE SLABS

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Farhad Aslani

February 2014

To My Family

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LIST OF PUBLICATIONS

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LIST OF NOTATIONS

Chapter 3

γ	unit weight of concrete
ϕ	fibre inclination angle
λ, μ	coefficients of linear equation of the stress-strain curve
λ_f, μ_f	coefficients of linear equation of the SFRSCC stress-strain curve
κ_1	first proposed constant value for MOE prediction
κ_2	second proposed constant value for MOE prediction
η_1	first proposed constant value for TS prediction
η_2	second proposed constant value for TS prediction
μ_i	initial coefficient of friction
μ_{ss}	steady state value of the coefficient of friction attained at large pullout distances
σ_c	concrete stress
σ_{cf}	SFRSCC compressive stress
σ_{ctf}	SFRSCC tensile stress
ε	concrete strain
ε'_c	strain corresponding with the maximum stress f'_c
ε'_{cf}	strain at peak stress of SFRSCC
ε^*	corresponding strain to the 0.85 f_{ctf}
ε_{ct}	tensile concrete strain
ε_f	SFRSCC strain
τ_{max}	maximum bond strength
$\tau_{max(app)}$	maximum apparent bond shear strength
$\tau_{f(app)}$	fibre apparent bond shear strength
τ_f	fibre bond shear strength
τ_u	ultimate bond strength
a	radius of fibre
c	concrete cover

c (fibre)	a constant that governs the rate at which the coefficient of friction decays with increase in pullout distance
d_b	diameter of the steel bar
d_f	diameter of fibre
E_c	modulus of elasticity of concrete
E_{cf}	modulus of elasticity of SFRSCC
E_{sec}	secant modulus of elasticity
E_{secf}	secant modulus of elasticity of SFRSCC
f	snubbing friction coefficient
f'_c	maximum compressive strength of concrete
f'_{cf}	compressive strength of SFRSCC
f'_{cy}	maximum compressive strength of cylinder concrete specimens
f'_{cu}	maximum compressive strength of cube concrete specimens
f_{cr}	modulus of rupture of concrete
f_{ct}	tensile strength of concrete
f_{ctf}	tensile strength of SFRSCC
k	spalling coefficient and ϕ is in radians
l_d	embedded length of the steel bar
l_f	length of fibre
l_f/d_f	aspect ratio
n	material parameter that depends on the shape of the stress-strain curve
n_f	SFRSCC parameter that depends on the shape of the stress-strain curve
n_1	modified material parameter at the ascending branch
n_{1f}	modified SFRSCC parameter at the ascending branch
n_2	modified material parameter at the descending branch
n_{2f}	modified SFRSCC parameter at the descending branch
p_{d1} and p_{d2}	fibre pullout distances
$P_{p_{d1}}$ and $P_{p_{d2}}$	fibre pullout loads corresponding to pullout distances p_{d1} and p_{d2}
P_m	measured fibre pullout load
R.I.	fibre reinforcing index
s, s_1, s_2, s_3	slip related to pullout bond test

$U_{peak}(\phi)$	peak slip displacement corresponding to the peak load with the inclination angle ϕ
V_f	fibre volume fraction
W_p	work of fibre pullout

Chapter 4

α	coefficient representing the influence of the cement type
β	represents time dependency of drying shrinkage
γ	coefficient representing the influence of the cement and admixtures type
η	constant related to compressive strength and water content
κ	conventional scalar damage index
μ, λ and α	parameters to be obtained from a least square minimization procedure
β_{sc}	coefficient which depends on the type of cement
σ'_{cp}	creep stress unit
ε'_{sh}	final value of shrinkage strain
$\varepsilon'_{ds\rho}$	the final value of drying shrinkage strain
$\varepsilon'_{ds\infty}$	final value of drying shrinkage
$\varepsilon'_{as\infty}$	final value of autogenous shrinkage strain
ε'_{cr}	final value of creep strain per unit stress
ε'_{bc}	final value of basic creep strain per unit stress
ε'_{dc}	final value of drying creep strain per unit stress
$(\varepsilon_{\mathrm{sh}})_{\mathrm{u}}$	ultimate shrinkage strain
$\varepsilon_e(t)$	instantaneous strain
$\varepsilon'_{cs}(t,t_0)$	shrinkage strain of concrete from age to t
$\varepsilon'_{ds}(t,t_0)$	drying shrinkage strain of concrete from age to t
$\varepsilon'_{as}(t,t_0)$	autogenous shrinkage strain of concrete from age to t
$\varepsilon'_{sc}(t,t_0)$	shrinkage strain of concrete from age of t_0 to t
$\varepsilon'_{as}(t,t_0)$	autogenous shrinkage strain of concrete from the start of setting to age t
$\varepsilon'_{cc}(t, t', t_0)$	creep strain
Δt_i	number of days where the temperature T prevails
$T(\Delta t_i)$	temperature (°C) during the time period Δt_i
c	cement

c/p	cement to powder ratio
f'_c	compressive strength
$f'_{c,28d}$	compressive strength at the age of 28 days
f_{cm}	mean compressive strength of concrete at the age of 28 day
f_{cmo}	10 MPa
$f_{cm}(t)$	mean value of compressive strength at time t
f	constant based on the duration of curing
h_0	100 mm
h	notional size of member (mm)
RH_0	100%
RH	relative humidity (%)
s' and n	parameters that have to be specifically calibrated for each SCC concrete mix by using experimental results
t_1	1 day
t_0	effective age (days) of concrete at the beginning of drying
t'	effective age (days) of concrete at the beginning of loading
t	effective age (days) of concrete during loading respectively
T_0	1 °C
v/s	volume to surface ratio
w	water
w/c	water to cement ratio

Chapter 5

α and β	empirical constants related to compressive strength model
η and μ	empirical constants related to modulus of elasticity
γ and λ	empirical constants related to tensile strength
ψ and ϕ	empirical constants related to modulus of rupture
ω and ρ	empirical constants related to energy dissipated under compression
χ, ξ	coefficients of linear equation of stress-strain curve
σ_c	concrete stress
ε	concrete strain
ε'_c	strain corresponding with the maximum stress f'_c

ε_u	ultimate deformation
E_c	modulus of elasticity
E_{cN}	N-SCC mix modulus of elasticity
E_{cfD}	D-SCC mix modulus of elasticity
E_{cfS}	S-SCC mix modulus of elasticity
E_{cfDS}	DS-SCC mix modulus of elasticity
E_{sec}	secant modulus of elasticity
f'_c	maximum compressive strength of concrete
f'_{cN}	N-SCC mix compressive strength
f'_{cfD}	D-SCC mix compressive strength
f'_{cfS}	S-SCC mix compressive strength
f'_{cfDS}	DS-SCC mix compressive strength
f_{ctN}	N-SCC mix tensile strength
f_{ctfD}	D-SCC mix tensile strength
f'_{ctfS}	S-SCC mix tensile strength
f'_{ctfDS}	DS-SCC mix tensile strength
f_{crN}	N-SCC mix modulus of rupture
f_{crfD}	D-SCC mix modulus of rupture
f_{crfS}	S-SCC mix modulus of rupture
f_{crfDS}	DS-SCC mix modulus of rupture
G_c	energy dissipated under compression
G_{cN}	N-SCC mix energy dissipated under compression
G_{cfD}	D-SCC mix energy dissipated under compression
G_{cfS}	S-SCC mix energy dissipated under compression
G_{cfDS}	DS-SCC mix energy dissipated under compression
n	material parameter that depends on the shape of the stress-strain curve
n_1	modified material parameter at the ascending branch
n_2	modified material parameter at the descending branch

Chapter 6

τ_b	bond shear stress
M_s	in-service bending moment

M_{cr}	cracking moment
kd	compression chord of depth
b	width
A_{st}	tensile reinforcement of area
A_{ct}	area of tensile concrete
d	depth
I_{cr}	second moment of area about the centroidal axis
σ_{ct}	uniform tensile stress of concrete
b^*	width of the section at the level of the centroid of the tensile steel
ρ	tensile reinforcement ratio
n	modular ratio
M	applied moment
f_y	steel yield stress
f_{ct}	direct tensile strength of the concrete
λ_1	load duration factor
λ_2	reduction in bond stress as the steel stress σ_{st1} factor
λ_3	significant increase in bond stress factor
ρ_{tc}	reinforcement ratio of the tension chord
d_b	reinforcing bar diameter
s_{min}	minimum crack spacing
s_{max}	maximum crack spacing
$(w_i)_{tc}$	instantaneous crack width
k_{cover}	a term to account for the dependence of crack width on the clear concrete cover
w_{max}	maximum crack width
l_{es}	transfer length
ε_{sm}	mean steel strain
ε_{cm}	mean concrete strain
σ_{cf}	stress in the fibre reinforced concrete
$\sigma^i_{cf,cr}$	imaginary cracking stress of the fibre reinforced concrete
τ_{sm}	average bond stress over load transmission length

E_s	modulus of elasticity of reinforcing bar
ρ_s	reinforcing ratio of steel reinforcement
α_b	shape coefficient of strain courses
α_E	ratio of the modulus of elasticity of steel to the modulus of elasticity of concrete
f_R	relative rib area of the rebars
σ_s	stress in the reinforcing bar at a crack
F	applied load
A_s	cross-sectional area of the steel bars
G_f	fracture energy of the concrete matrix
σ_{cf0}	maximum post-cracking stress
w_0	crack width corresponding to maximum post-cracking stress
σ_{cf0}	maximum post-cracking stress
η	coefficient of fibre orientation
g	coefficient of fibre efficiency
ρ_f	volume fraction of fibres
l_f	fibre length
d_f	fibre diameter
τ_{fm}	mean fibre-matrix bond stress
f_{ctm}	mean tensile strength of the plain concrete matrix
E_f	modulus of elasticity of the fibres
$\sigma^{i}_{cf,cr}$	maximum stress of the ascending fibre phase
Chapter 7	
α_b	shape coefficient of strain courses
$\alpha_{E,s}$	ratio of the modulus of elasticity of steel to the modulus of elasticity of concrete
$\alpha_{E,f}$	ratio of the modulus of elasticity of fibre to the modulus of elasticity of concrete
η	fibre orientation coefficient
$\varepsilon_{f,shr}$	shrinkage shortening of the fibres
ρ_s	reinforcing ratio of steel reinforcement

ρ_f	fibre content
ρ_{tc}	reinforcement ratio of the tension chord
σ_{cf}	stress in the fibre reinforced concrete
τ_b	bond shear stress
τ_{sm}	average bond stress over load transmission length
A_{st}	tensile reinforcement of area
A_{ct}	area of tensile concrete
b	width
d_b	reinforcing bar diameter
E_s	modulus of elasticity of reinforcing bar
kd	compression chord of depth
M_{cr}	cracking moment
M_s	in-service bending moment
s^*	final maximum crack spacing

Chapter 8

α_e	modular ratio = E_s / E_c
α_b	shape coefficient of strain courses
α_E	ratio of the modulus of elasticity of steel to the modulus of elasticity of concrete
β	empirical coefficient to assess the mean strain over $l_{s,max}$
β_{ac}	ratio of the distances from the neutral axis to the extreme tension fibre
β_{ec}	coefficient relating the average crack width to the design value
β_{mc}	empirical coefficient to assess the average strain within $l_{s,max}$
ϕ	diameter of the steel fibre
ρ	relaxation coefficient
ρ_{ef}	effective steel ratio
φ	creep coefficient
σ_s	steel stress
σ_{sr}	maximum steel stress in a crack in the crack formation stage
σ_{cti}	uniform average tensile stress
τ_{bi}	short-term bond stress

τ_{bm}	mean bond strength
τ_{sm}	average bond stress over load transmission length
ε_{cm}	mean strain in the concrete between the cracks
ε_{s2}	maximum steel strain at the crack
ε_{sr2}	steel strain at the crack
ε_{cs}	free shrinkage strain of concrete
ε_{sm}	mean strain in the reinforcement at the design loads
η_r	coefficient taking account of shrinkage contribution
A_{ct}	cross-sectional area of concrete in the tensile zone
$A_{c,eff}$	effective area of the tensile concrete surrounding the tensile reinforcement of depth
A_e	effective tension area of concrete surrounding the flexural tension reinforcement
$A_{s,min}$	minimum tensile reinforcement area
A_{st}	cross-sectional area of tensile steel reinforcement
c	clear cover to the longitudinal reinforcement
d	depth to the tensile reinforcement
d_b	bar diameter
d_c	distance from centre of bar to extreme tension fibre
d_n	depth of compression zone in a fully cracked section
D	overall depth of a cross-section
E_s	steel modulus of elasticity
f_{ct}	concrete matrix tensile strength
$f_{ct,eff}$	mean value of the axial tensile strength of concrete at the time cracking
f_{ctm}	mean value of axial tensile strength
F_{cr}	cracking force
f_{Fts}	steel fibre tensile strength
f_s	maximum stress permitted in the reinforcement immediately after crack formation
f_y	steel bar yield stress
k_t	factor that depends on the duration of load

k_1	coefficient depending upon bond quality
k_2	coefficient depending upon the shape of the strain diagram
l_{es}	transfer length
$l_{s,max}$	length over which slip between steel and concrete occurs
L	length of the steel fibre
M_{cr}	cracking moment
M_{max}	maximum moment
n_b	number of reinforcing bar
s	bar spacing
s_{rm}	average crack spacing
$s_{r,max}$	maximum crack spacing
w_k	maximum crack width
w_m	average crack width
w_{max}	maximum crack width

LIST OF ACRONYMS

AEA	air-entraining admixtures
CA	coarse aggregate
CC	conventional concrete
CD	casting direction
CRI	concrete research institute
CRC	conventional reinforced concrete
CS	compressive strength
CSSC	compressive stress-strain curve
c/p	cement to powder ratio
EFA	Eraring Fly Ash
FA	fine aggregate
FCL	first crack load
FCD	first crack deflection
FEM	finite element method
FRC	fibre-reinforced concrete
FRSCC	fibre-reinforced self-compacting concrete
FTS	flexural tensile strength
H	horizontal casting direction
HMR	high moment region
HRWR	high range water reducer
GGBFS	ground granulated blast furnace slag
LVDT	linear variable displacement transducer
MOE	modulus of elasticity
MOR	modulus of rupture
RH	relative humidity
RC	reinforced concrete
RVE	representative volume element
SC	slag cement

SCC	self-compacting concrete
SFC	super flowable concrete
SFRC	steel fibre-reinforced concrete
SFRSCC	steel fibre reinforced self-compacting concrete
SHCC	strain hardening cementitious composites
SLC	shrinkage limited cement
SP	superplaticizers
SUCST	specimen utilized in the compressive strength test
TS	tensile strength
UHPFRC	high and ultrahigh performance fibre reinforced concrete
V-D	vertical down casting direction
V-U	vertical up casting direction
w/c	water-cement ratio
w/cm	water-cementitious materials ratio
VMA	viscosity modifying admixture
WHS	workplace health and safety
WR	water reducer

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ABSTRACT

Developments in concrete technology provide engineers, designers, suppliers and contractors with new methods of approaching engineering problems. Many of these developments are engineered solutions to technical and commercial problems, by either improving the current practices or overcoming limitations in the existing technology. One of the developments is Self-Compacting Concrete (SCC). SCC refers to a 'highly flow-able, non-segregating concrete that can be spread into place, fill the formwork, and encapsulate the reinforcement without the aid of any mechanical consolidation' as defined by the American Concrete Institute (ACI). SCC is regarded as one of the most promising developments in concrete technology due to significant advantages over Conventional Concrete (CC). Many different factors can influence a decision to adopt SCC over CC ranging from structural performance to associated costs. These decisions should be well informed and based on a sound understanding of such factors.

In addition, Fibre Reinforced Self-Compacting Concrete (FRSCC) is a relatively new composite material which congregates the benefits of the SCC technology with the profits derived from the fibre addition to a brittle cementitious matrix. Fibres improve many of the properties of SCC elements including tensile strength, ductility, toughness, energy absorption capacity, fracture toughness and cracking.

For a structure (made by CC, SCC and FRSCC) to remain serviceable, crack widths must be small enough to be acceptable from an aesthetic point of view, to avoid waterproofing and deterioration problems by preventing the ingress of water and harmful substances. Crack control is therefore an important aspect of the design of reinforced concrete structures at the serviceability limit state. Limited researches have been undertaken to understand cracking and crack control of SCC and FRSCC members. Since, the time-dependent mechanisms of SCC and FRSCC are still not completely understood; a reliable and universally accepted design procedure for cracking and crack control of SCC and FRSCC members has not been developed yet. There exists a need for both theoretical and experimental research to study the critical factors which affect the time-dependent cracking of SCC and FRSCC members.

In this study cracking caused by external loads in reinforced SCC and FRSCC slabs is examined experimentally and analytically. The mechanisms associated with the flexural cracking due to the combined effects of constant sustained service loads and shrinkage are observed. One of the primary objectives of this study is to develop analytical models that accurately predict the hardened mechanical properties of SCC and FRSCC. Subsequently, these models have been successfully applied to simulate time-dependent cracking of SCC and FRSCC one-way slabs.

Series of tests on eight prismatic, singly reinforced concrete one-way slabs subjected to monotonically increasing loads or to constant sustained service loads for up to 240 days, were conducted. An analytical model is presented to simulate instantaneous and time-dependent flexural cracking of SCC and FRSCC members. It should be emphasized that any analytical model developed for calculation of crack width and crack spacing of reinforced SCC and FRSCC slabs must be calibrated by experimental data and verified by utilizing Finite Element Method (FEM). The analytical predictions of crack width and crack spacing for the SCC and FRSCC one-way slabs are in reasonably good agreement with the experimental observations.