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Predicting the Compressive Strength and the Optimum Water to Binder Ratios by Packing Density Theory for High Strength Self-Compacting Concrete

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Abstract: *In concrete technology, the new particle packing models and theories makes it possible to design different types of concrete, such as high strength concrete and self-compacting concrete. This research aims to apply packing density theory of compressible interactions Packing Model (CIPM) on high strength self-compacting concrete mixes. Mixes were selected with different cement contents and different sizes of aggregate to applying the (CIPM) packing density model. The output parameters were calculated by packing density theory, which used to predict the compressive strength and reduce the water contentimprove the compressive strength of the mixes with achieving the workability in the reference mixes as possible within the limits of self-compacted concrete specifications. The results showed that using appropriatewater amount improvedthe packing of concrete and contributed to spread the cement content to encapsulate the aggregates granules, also decreased the air volume in the concrete mix.*

Keywords: *Self compacting concrete, packing density, slump flow.*

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I. Introduction

American Concrete Institute (ACI) defines self-compacted concrete (SCC) as the concrete that meets special performance and uniformity requirements that may not always be obtained using conventional ingredients, normal mixing procedures and typical curing practices[1].The FIP/CEB defines HSC as "a concrete having a minimum 28-day compressive strength of 60MPa"[2].A high cement content in a mix does not contribute to greater strength than the required design strength[3].For the concretemix, the basic proportioning strategy is to design the granular mix with the sake of a minimum porosity. Then, the composition of the matrix was fixed with regard to final strength and durability, low water-cement ratio being the key parameter [4].Several packing models were developed such as the Furnas model (1929) [5], the Toufar model (1976)[6], the Linear-Mix Packing Model (1991)[7], the Dewar model (1999)[8], the Schwanda model (2000)[9] and the Linear Packing Density Model (1999) from F. De Larrard[10].The F. De Larrard model were considered the best applicable packing model, which are taking into account all different particle sizes. F. De Larrard packing theory was modified by Sonja finnes[11], to be the packing theory of compressible interactions Packing Model (CIPM) which applied in this search.

II. Packing Density Theory

The packing density of particles (α_t), which defined as the ratio of the solid volume of the particles to the bulk volume occupied by the particles, is a fundamental parameter governing the properties of many materials made from particles [4].The (CIPM) packing density parameters outputs were included as ; the amount of solids in the mix in a unit volume (φ_{mix}), total packing density of a mix (α_t) which was used to evaluate the properties of concrete mixes. In addition, spacing cement factor (CSF) is used to evaluate the compressive strength and the relation(φ_{mix}/α_t) betweenpartial volume of all the particles to the volume of the calculated packing density to evaluate the workability. Sonja Finesse [4] proved that the relation between strength and Cement Spacing Factor (CSF) makes it possible to predict the strength of mixesin which the amount of cement in the mix and is the maximum volume that cement could occupy in presence of the other particles. The cement spacing factor (CSF) which used toevaluate strength of normal concrete,was described by Sonja Finnesas shown in equation (1)

$$f_c=366(CSF)-231 \quad (1)$$

The relation between (φ_{mix}/α_t) and the slump value of normal concrete mixes can be used to estimate the required amount of water in a mix at its prescribed consistency.In that case design values for (φ_{mix}/α_t) are required which comply with the desired workability[4]. (φ_{mix}/α_t) andflowability of concrete mixeswere described by Sonja finnes equation as as mentioned in equation (2)

$$\text{Slump flow}=-8888(\varphi_{mix}/\alpha_t) + 4221(\varphi_{mix}/\alpha_t)^2 +4767 \qquad (2)$$

These equations were compared with equations results fromthe investigatedmixes in this search.

III. Research Significance

The aim of the experimental program is to applythe theory of compressible interactions Packing Model (CIPM)that applied on normal concrete on high strength self-compacting concrete. The compressive strength and workability with optimum water to binder ratio were evaluatedanalyticallyand experimentally.Twelve reference mixeswere selected and experimented based on (CIPM) packing density model by Sonja Finesse [4], all outputs results wereobtained and discussed. The predicted strength and flowability equations were calculated and compared with Finnes equations. The reduction of water to binder ratio and replacement cement content by supplementary cementitious materials were the focus of this paper.

IV. Materials And Methods

The following materials selected and tested according to the Egyptian standard specifications; the materials used in this study are as follow:

- **Cement** isCEM I (Type52.5 N) produced by the Sinai cement factory. It satisfies with the requirements of the Egyptian Standards [(ESS. 4657-1/2009)] [12].
- **Coarse aggregate:** it is crushed dolomite from North Sinai quarry, has maximum size and specific gravity of 12.5 mm, and 2.70 respectively, which satisfies the Egyptian Standard Specification (ESS. 1109\ 2010)][13].
- **Fine aggregate:** It is natural siliceous sand from North Sinai quarry, has specific gravity of 2.50, which satisfies the Egyptian Standard Specification (ESS. 1109\ 2010)] [13].
- **Water:** it is ordinary Potable tap water.
- **supplementary cementitiousmaterials:** Three types of supplementary materials used are :
  (a) Silica fume complying with the requirements of ASTM C1240-15[14].
  (b) Fly ash complying with the requirements of ASTM C618-15[15].
  (c) Waste North Sinai marble powder specific gravity 2.5.
- **Superplasticizer:** it is a high range water reducing admix which has commercial name of (SikaViscocrerte-3425) complying with the requirement of ASTM C494 Type G [16].

The slump flow testis used for testing the fresh concrete to check its properties for flowability. Self-compacted concrete mixes were compiledwith the European guidelines for self-compacted concrete. The constituent materials were tested and compared with the requirements of ASTM and Egyptian standard specifications. The compressive strength specimens were cubes (100 x100 x100mm) and tested at 28 days. The curing was in water at room temperature.

V. Concrete Mixes

High strength self-compacted concrete with different amount of aggregates volume and different supplementary cementitious materials (SCM)contentswere selected from references mixes as shown in table(1). These mixeswere modified by reducing the amount of water for these reference mixes. The modification of these mixes did not include cement, aggregates and supplementary materials contents but the change occurred in water content and superplasticizer as shown in table (2). The constituent materials of the selected mixes should be comply limits of self-concrete according to EFNARC-2005[17] and gain high strength. The reference mixes(Rf)were in formula and the experimented one were in (Mix) formula.

Table (1), Mix proportions of reference mixes by weight.

Quantity of material by weight (Kg/cubic meter)									Reference Concrete results	
Mix No	Cement content	Coarse aggregate	Fine aggregate	Mineral Admix			Water	SP	Compressive Strength (MPa) after28 days	Slump flow (mm)
				Silica fume	Fly ash	Marble powder				
Rf1[18]	600	700	900	0	0	0	200	12	84	680
Rf 2[19]	550	780	850	0	55	0	192	16.5	96	710
Rf 3[18]	540	700	900	60	0	0	170	12	90	712
Rf 4[20]	525	850	850	50	75	0	180	14	90	660
Rf 5[21]	522	722	867	78	0	0	158.3	9.62	81	742
Rf 6[22]	500	800	800	100	0	0	192	12	87	710
Rf 7[23]	479	880	715	78	48	0	177	3	61	685
Rf 8[24]	455	708	760	0	45	100	177	9	60	700
Rf 9[25]	437	927	1048	163	0	0	178	6	75	710
Rf 10[18]	420	700	900	0	180	0	190	4.09	70	750
Rf 11[24]	406	1020	766	0	94	100	180	9.6	85.2	700
Rf 12[26]	400	700	853	0	0	200	165	3.2	70	670

Table (2),Mix proportions after modifying water and superplasticizer contents

Quantity of material by weight (Kg/cubic meter)								
Mix No	Cement content	Coarse aggregate	Fine aggregate	Mineral Admix			Water	SP
				Silica fume	Fly ash	Marble powder		
Mix1	600	700	900	0	0	0	190	14
Mix2	550	780	850	0	55	0	182	14.5
Mix3	540	700	900	60	0	0	165	15
Mix4	525	850	850	50	75	0	167	13
Mix5	522	722	867	78	0	0	158.3	16
Mix6	500	800	800	100	0	0	186	13.5
Mix7	479	880	715	78	48	0	171	11
Mix8	455	708	760	0	45	100	169	8.5
Mix9	437	927	1048	163	0	0	172	14
Mix10	420	700	900	0	180	0	179	12
Mix11	406	1020	766	0	94	100	169	9
Mix12	400	700	853	0	0	200	165	8

VI. Results And Analysis

6.1Packing Optimization of reference mixes

To show how the principle works, the packing density parameters wereused to compare the compressive strength and workability results of reference mixesasshown in table (3). All concrete mixeswere calculated as the same of constituent materials content as shown in table (1).

Table (3) packing density output parameters of reference mixes

Mix No.	α_t	$\varphi_{mix,}$	$\varphi_{mix}/\ \alpha_t$	CSF
Rf1	0.91	0.810	0.833	0.845
Rf2	0.91	0.828	0.871	0.845
Rf3	0.92	0.818	0.838	0.838
Rf4	0.93	0.878	0.879	0.835
Rf5	0.89	0.815	0.871	0.835
Rf6	0.91	0.803	0.861	0.835
Rf7	0.92	0.821	0.841	0.835
Rf8	0.92	0.777	0.801	0.833
Rf9	0.91	0.975	0.976	0.829
Rf10	0.92	0.834	0.856	0.827
Rf11	0.92	0.901	0.933	0.828
Rf12	0.90	0.818	0.822	0.832

The packing density results were ranged between 0.89 and 0.93, the best results of packing when approach to be (1). When packing density values increase, consequentlythe other outputs parameters of packing increase so, when packing parameters improved, it would contributeto achieve good results of concrete properties. Spacing cement factor (CSF) one of these output results thatused to evaluate the compressive strength.

6.2Water Demand

Packing density outputs used to predict the necessary amount of water within the mix thatcould be reduced to gain high strength with keeping workability as possible. The excess amount of water, taken out of the mixhas a great influence on the packing density (α_t). As shown in table (4) the value for (φ_{mix}), and (α_t) could be calculated and then it is possible to calculate the lower amount of water. The results showed in the table were calculated from equation (3) and (4)

$$\varphi_{mix,optimized} = \frac{\varphi_{mix,reference}}{\alpha_{t,reference}} \alpha_{t,optimized} \quad (3)$$

$$\varphi_{mix,optimized} = \frac{V_{tot} - V_w}{V_{tot}} \quad (4)$$

Table (4) lower amount of water in comparison to the reference mix

Mix No.	(V_W) Reference	(W/B)	(V_W)Modified	(W/B) Modified
Rf1	200	0.33	188	0.31
Rf2	192	0.32	180	0.30
Rf3	170	0.28	153.5	0.26
Rf4	180	0.30	168	0.28
Rf5	158.3	0.26	148.68	0.25
Rf6	192	0.32	187.91	0.31
Rf7	177	0.30	168	0.28
Rf8	177	0.30	171	0.29
Rf9	178	0.30	168.4	0.28
Rf10	190	0.32	187	0.31
Rf11	180	0.30	166	0.28
Rf12	165	0.28	161.8	0.27

From results shown in tables (3) and (4), the ratio (φ_{mix}/α_t) and the value for the flow were correlated to each other. The relation between the ratio (φ_{mix}/α_t) and s the slump flow were checked.

The results of the experimented mixeson fresh concrete and packing optimized on the workability were shown in table (5).Results showed that slump flow results ranged between 600 to 720 mm and these results were within the acceptable limits of SCC. Results thatwere obtained from tables (1) and (5) showed that when water to binder ratio reduced, the slump flow decreased. Decreasingof the slump flow results were ranged between 2.94% and 15.5%.

Table (5) Output parameters aftermodifying concretemixescalculated by (CIPM)

Mix No.	(α_t)	(φ_{mix}/α_t)	Slump flow (mm)
Mix1	0.95	0.98	660
Mix 2	0.95	0.98	640
Mix 3	0.95	0.98	670
Mix 4	0.947	0.974	640
Mix 5	0.90	0.897	680
Mix 6	0.948	0.974	660
Mix 7	0.947	0.974	720
Mix 8	0.948	0.974	650
Mix 9	0.947	0.973	600
Mix 10	0.975	1	640
Mix 11	0.975	1	620
Mix 12	0.90	0.9	700

Figure (1) shows the relation between slump flow and the ratio (φ_{mix}/α_t). The ratio (φ_{mix}/α_t) ranges between 0.897 and 1. Equation of Sonja Fennisthat mentioned in eq(2) did not give results configure with HSC results. From fig. (1), Eq.(5) could be obtained to present the relation between slump flow and the ratio (φ_{mix}/α_t) for HSSCC.Equation (5) gives adequate results compared to that indicated form experimental test results.

$$\text{Slump flow} = 15902(\varphi_{mix}/\alpha_t) - 8738.4(\varphi_{mix}/\alpha_t)^2 - 6543.8 \quad (5)$$

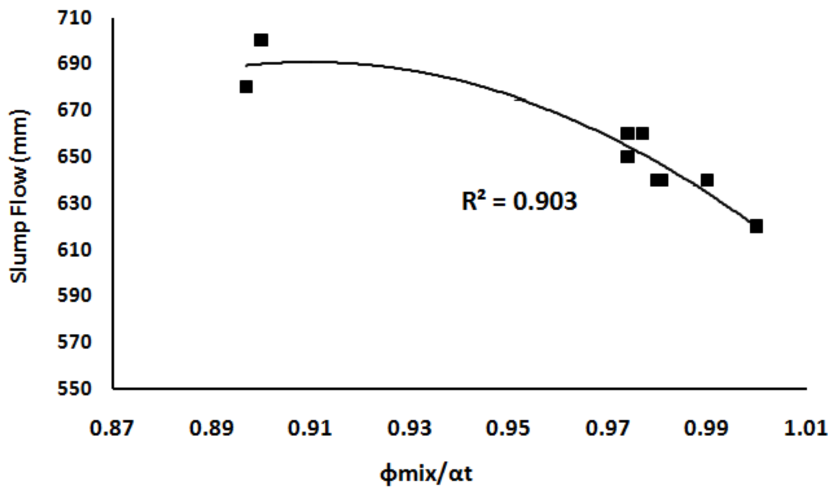

Figure (1) relation between workability parameters (φ_{mix}/α_t) and the slump flow of modified reference mixes.

6.5Compressive strength

Results of spacing cement factor(CSF) for improved mixes andthe laboratory measured compressive strength of the improvedmixeswere given in table (6).The results were depicted by plotting the compressive strength with spacing cement factor as shown in Fig (2).

Table (6) Output parameters computed by (CIPM) packing density model and laboratory measured compressive strength

Mix No.	CSF Improved	(f_c) Measured
Mix1	0.94	70
Mix 2	0.94	70
Mix 3	0.946	74
Mix 4	0.94	67
Mix 5	0.842	68
Mix 6	0.941	71
Mix 7	0.940	68
Mix 8	0.938	62
Mix 9	0.946	66
Mix 10	0.940	69
Mix 11	0.943	72
Mix 12	0.829	55

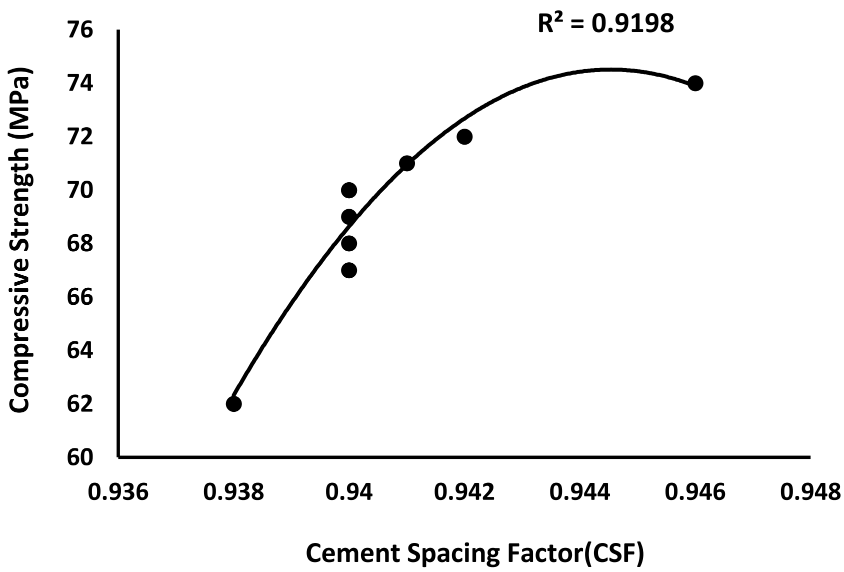

Fig (2) the relation between compressive strength and the cement spacing factor (CSF) for experimented mixes.

Equation of Sonja Fennisthat mentioned in eq(1) did not give adequate results. From fig.(2), Eq (6) could be obtained to present the relation between compressive strength and CSF for HSSCC.Equation (6) gives adequate results compared to that indicated form experimental test results.

$$\text{Compressive strength } (f_c) = 130799\ (CSF) - 77373\ (CSF)^2 - 55183 \qquad (6)$$

VII. Conclusions

The following conclusionscan be drawn;

1. The compressible interactions Packing Model (CIPM)was created based on normal strength concrete and the recent work proved that it is possible to apply the model in high strength self-compacting concrete mixes.
2. Predicting adequate water demand improves the packing density and gains high strength concrete with keeping the workability in self-compacted concrete limits.
3. Equations (5) and (6) give results closed to that indicated from laboratory while results indicated from Sonja Fenniswere inaccurate because Sonja Fennis equations were driven for normal strength concrete.

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