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Research paper

Effects of Mineral Admixtures on the Mechanical Properties of Self Compacting Concrete

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Abstract

The objective of this study was to evaluate the properties of Self Compacting Concrete (SCC) produced by locally available materials and the influence of types and dosages of the mineral admixtures on these properties in fresh and hardened phases. To achieve this objective, 7 different mixes of SCC were mixed, tested and evaluated. The results indicate that acceptable SCC mixtures can be created. The type of the mineral admixtures according to its pozzolanic activity has significant effects on the strengths of the studied SCC mixes especially at the 28 and 90 days ages. The excess fineness negatively affects the early age strengths, but it improves the later age strengths. Irregular particle-distribution system and the more dosage of the mineral admixtures negatively affect the strengths of the mixes. The modulus of elasticity of the mixes is slightly lower than that of conventional concretes. Non-destructive tests confirm an inference that there is less heterogeneity of the SCC.

Index Terms*: SCC, Mineral admixtures, Sustainability, Lime stone powder, High Reactive Metakaoline, Grinded Demolished Concrete, Hardened properties, Non destructive tests.*

1. Introduction

It was reported that the production of SCC in ready mix concrete plants have largely increased due to its advantages in consolidation, uniformity and reliability. Self-compacting Concrete is an innovative concrete that does not require any vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. Self-Compacting Concrete is a complex system that is usually proportioned with one or more additions and one or more chemical admixtures (Ramanathan 2013 [1]).
The way for a successful mix proportion of SCC is an obvious understanding of the functions of the various constituents in the mix and their influences on the fresh and hardened properties (Bonen. and Shah 2005 [2]). Because of their superior engineering and performance properties, mineral admixtures are normally contained in the production of high-strength and high-performance concrete (Gesoglu et al., 2009 [3]).
Recently, one of the main concerns of most countries is coming up with a low impact material to be used in construction which can meet the needs and desires of both contractors and consumers and at the same time fulfill the principles of a new but fast growing trend; sustainable development (Nima et al., 2011 [4]). In particular the need to decrease the overall CO2 production related to the use of cement in concrete (Bilodeau and Malhotra, 2000 [5]). Incorporation of more mineral and chemical admixtures might enable the concrete industry to reduce or even substitute General Portland cement which could lead to cleaner and less energy consuming, low impact building materials in the future (Nima et al., 2011 [4]).
This study aimed to evaluate the properties of SCC produced by locally available materials and the influence of types and dosages of the mineral admixtures on these properties in fresh and hardened phases.

2. Literature Review

2.1 Materials

The cement used in this study is Ordinary Portland Cement Type (I). This cement is tested and checked according to Iraqi specification No.5: 1984 [6]. Table (1) shows the grading of the fine aggregate, while Table (2) shows the grading of the crashed gravel of 10 mm maximum size

Table 1: Grading of Fine Aggregate

Sieve size (mm)	% Passing by weight	Limits of the Iraqi specification No.45/1984[7] (zone 2)
4.75	100	90-100
2.36	92.1	75-100
1.18	82.0	55-90
0.60	58.8	35-59
0.30	27.0	8-30
0.15	7.15	0-10
Fineness Modulus = 2.33		

Table 2: Grading of Coarse Aggregate

Sieve size (mm)	% Passing by weight	Limits of the Iraqi specification No.45/1984[7]
14	100	100
10	88.6	85-100
5	10.8	0-25
2.36	0	0-5

A copolymer-based superplasticizer, designed for the production of High Performance Concrete is used (Glenium 51). Three locally available types of mineral admixtures are used for the purpose of this study. Limestone powder (LSP) is locally named as “Al-Gubra”. It is a white grinding material from lime-stones excavated from different regions in Iraq, and usually used in the construction processes. In this work, a fine limestone powder, grinded by blowing technique, has been used. The fineness of the gained material is very high. The chemical composition of LSP is listed in Table (3). High Reactive Metakaoline (HRM) is a reactive aluminosilicate pozzolana produced by clinking China clay at temperatures of 700 – 900°C. In this work, the locally available China clay clinks in laboratory using the burning kiln of clinkering ability up to 1200°C, and the China clay is burned at 700°C for whole one hour then left to cool down. Pozzolanic activity index (P.A.I) of HRM with Portland cement is determined according to ASTM C311-17 [8]. HRM cement mortars that contain 10% HRM are tested, the w\p that satisfies flow 110±5mm is 0.40, and the dosage of superplasticizer is constant. The chemical and physical properties of HRM are listed in Table (4). Demolished concrete is collected from different samples, then grinded by locally special grinding machine by blowing, the same as LSP. In order to determine the (P.A.I) of Grinded Demolished Concrete (GDC) with Portland cement, the same procedure illustrated in the previous paragraph is adopted. The chemical and physical properties of GDC are listed in Table (5).

2.2 Concrete Mixes

In order to achieve the scopes of this study, the work is divided into seven mixes {Table 6}. EFNARC [9] first approach for mix design method is used, and then the proportions of materials modified after the evaluation by fresh tests have been done. The modifications are made according to EFNARC [9].

Table 3: Chemical Composition and Physical Properties of LSP Chemical Properties

Oxides	Content %
SiO_2	1.38
Fe_2O_3	0.12
Al_2O_3	0.72
CaO	56.1
MgO	0.13
SO_3	0.21
L.O.I	4.56
Physical Properties	
Fineness (Blain)	3100

Table 4: Chemical and physical properties of HRM Chemical Properties

Oxides	Content %
SiO_2	51.34
Fe_2O_3	2.30
Al_2O_3	41.65
CaO	3.00
MgO	0.17
SO_3	-
L.O.I	4.48
Physical Properties	
P.A.I	1.28
Fineness (Blain)	3400

Table 5: Chemical and physical properties of GDC

Oxides	Content %
SiO_2	50.74
Fe_2O_3	1.20
Al_2O_3	5.94
CaO	35.48
MgO	0.56
SO_3	1.50
L.O.I	4.50
Physical Properties	
P.A.I	1.32
Fineness (Blain)	3100

Table 6: Sets and Details of Mixes

	Refrence	Set 1			Set 2		
	C	L1	M1	D1	L2	M2	D2
W	170	170	170	170	170	170	170
C	500	450	450	450	350	350	350
LSP	-	50	50	50	150	150	150
HRM	-	50	50	50	150	150	150
GDC	-	50	50	50	150	150	150
S	778	778	778	778	778	778	778
G	890	890	890	890	890	890	890
SP	4	6	10	7	7	12	8
W/P	0.34	0.35	0.36	0.35	0.35	0.36	0.35

1-Values of water and S.P. in l/m^3, others in $kg\backslash m^3$. 2- w\p = water to poweder (cement+mineral admixture) ratio.

2.3 Tests of Hardened SCC

In the hardened phase, the compressive strength test at 1, 7, 28 and 90 day ages are done. All specimens are demolded after 24 ± 4 h, marked and cured in water at 22 ± 3ºC until they are taken out just before testing. In order to find a correlation between the strengths of the different specimen shapes, standard cubes measuring 150 mm and cylinders measuring (150 × 300 mm) are used within this test.

3. Results And Discussion

3.1 Compressive Strength

Tables (7) and (8) show the average results of the compressive strength tests at 1, 7, 28 and 90 days gained from cubes and cylinders respectively. For conventional concretes, the ratio of cube to cylinder compressive strength is about 1.25, as stated by Neville (2011) [10], or in the range 1.176 – 1.280, as stated by Hawraa (2003) [11]. The ratios of (fcu / fcy) for all mixes are calculated for all ages and listed in Table (7). The ratios of (fcu / fcy) at the age of 28 days are in the range of (1.05 to 1.13). These ratios illuminate that they are lower than the ratios of the conventional concretes. Consequently, the compressive strength is less related to the slenderness of the specimens.
Figure (1) shows a comparison between the values of fcu for the mixes. Developments of fcu for the same mixes with time are plotted in Figure (2). These two figures clearly illustrate that the addition of 10% of mineral admixtures as a replacement from the weight of cement, significantly affects the compressive strength of mixes in all ages. The results of fcu vary according to the type of the mineral admixture and the age of the specimens. At 1 and 7 days ages, mixes with GDC has the highest compressive strength followed by mixes

with LSP then those with HRM. At 28 and 90 days ages, the mixes with HRM jumps to the second position. This behavior clarifies the highly pozzolanic effects of GDC and HRM. The low strength of mix M1 and M2 at the early ages can be explained with the higher dosage of superplasticizer in the mixes which delays the setting action of concrete. Compared with the strengths L1, M1 and D1 mixes, fcu of L2, M2 and D2 mixes are lower, see Figure (1). This behavior is expected due to the decrement of the cement content in the mixes in set 3 to 70% by weight of powder. However, the mixes that have pozzolanic activity provide reasonable compressive strength, and this can become an economic factor in producing SCC.

Table 7: Results of Compressive Strength (MPa) for 150mm cubes (fcu)

Mix	1 day	7 days	28 days	90 days
C	28	51	75	88
L1	25	37	63	85
M1	20	45	80	109
D1	30	53	85	116
L2	14	35	52	70
M2	10	40	65	89
D2	17	42	72	97

Table 8: Results of Compressive Strength (MPa) for (150 × 300 mm) cylinders (fcy)

Mix	1 day	7 days	28 days	90 days
C	26	47	70	80
L1	23	34	59	78
M1	19	40	73	99
D1	28	49	78	106
L2	13	32	48	64
M2	9	37	59	83
D2	15	39	67	90

Table 9: Ratios of fcu / fcy

Mix	1 day	7 days	28 days	90 days
C	1.08	1.09	1.07	1.10
L1	1.09	1.09	1.07	1.09
M1	1.05	1.13	1.10	1.10
D1	1.07	1.08	1.09	1.09
L2	1.08	1.09	1.08	1.09
M2	1.11	1.08	1.10	1.07
D2	1.13	1.08	1.07	1.08

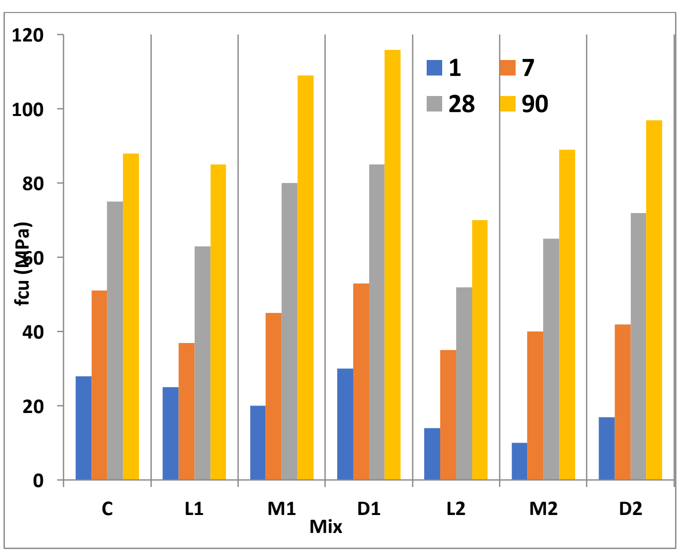


Fig. 1: fcu for mixes

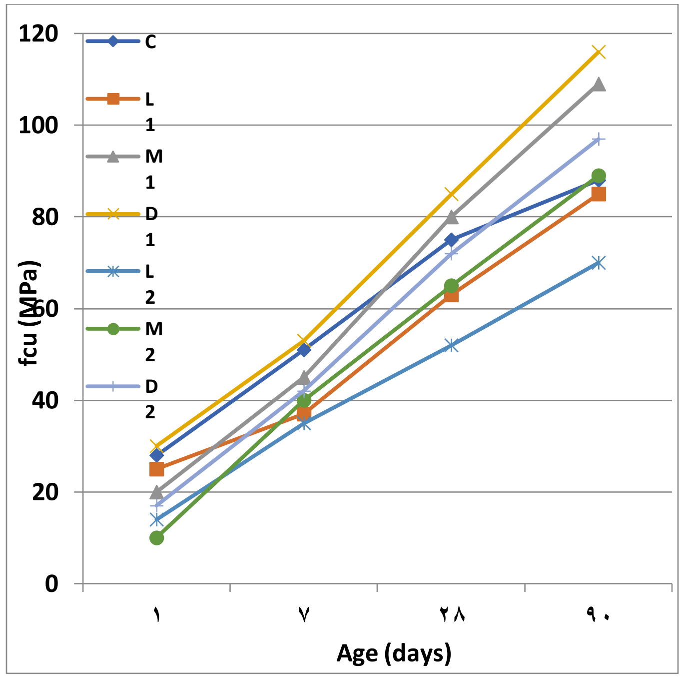


Fig. 2: Development of fcu with Time

3.2 Splitting Tensile Strengths

The results of the splitting tensile strength (f_t) tests are listed in Table (10) and plotted in Figure (3) in descending manner.

Table 10: Results of Splitting Tensile Strength (f_t) (MPa)

Mix	f_t
C	4.7
L1	4.3
M1	4.9
D1	5.1
L2	3.9
M2	4.3
D2	4.6

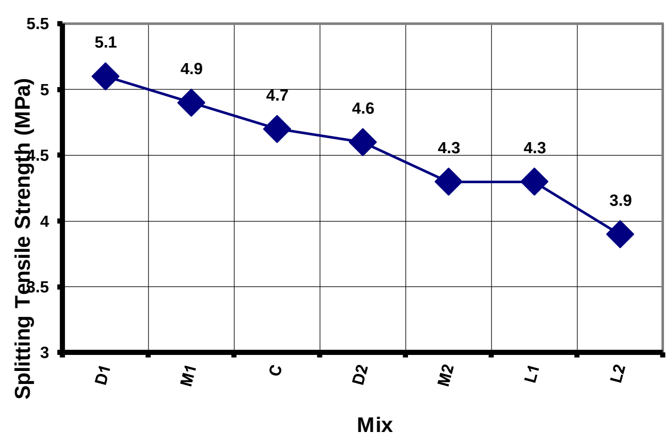
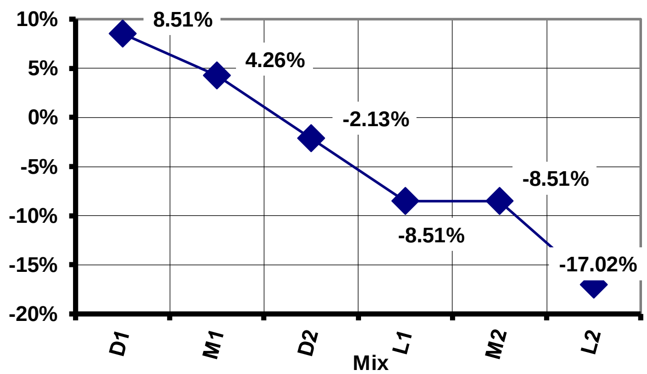


Fig. 3: Results of Splitting Tensile Strength

The effects of the mineral admixtures changes (type, fineness, dosages and ternary blend of powder) on the splitting tensile strength are summarized in Figure (4) which shows the values of percent variance (PV) between the results of the mixes are used of (f_t) in descending manner. The results in this figure illustrate that the (f_t) is significantly affected by the type of the mineral admixtures. The mixes which contain GDC as a mineral admixture have better results followed by mixes that contain HRM and LSP in sequence. This significant effect of the type refers to the pozzolanic activity of the mineral admixtures which improve the strengths of the mixes. Thus, it can be inferred that this effect of type or the pozzolanic activity minimizes the effects of the other changes of the mineral admixtures



Neville [10] stated that the two types of strength (compressive and tensile) are closely related. The ratios of (f_t) to (f_{cy} at 28 days age) are calculated and listed in Table (11). The values of these ratios are between 6.54% and 8.13%. These ratios are within the usual range which is between 6% and 20%, as stated by Avram et al. (1981) [12].

Table 11: Ratios of (f_t) to (f_{cy})

Mix	f_t / f_{cy}
C	6.71%
L1	7.29%
M1	6.71%
D1	6.54%
L2	8.13%
M2	7.29%
D2	6.87%

The ratios in Table (11) are plotted in Figure (5). From this figure, the following equation is derived:

$$f_t = 0.48 f_{cy}^{0.54}$$

In comparison with the following relationship stated by Neville [10], the SCCs relationship seems to be close.

$$f_t = 0.3 f_c^{0.67}$$

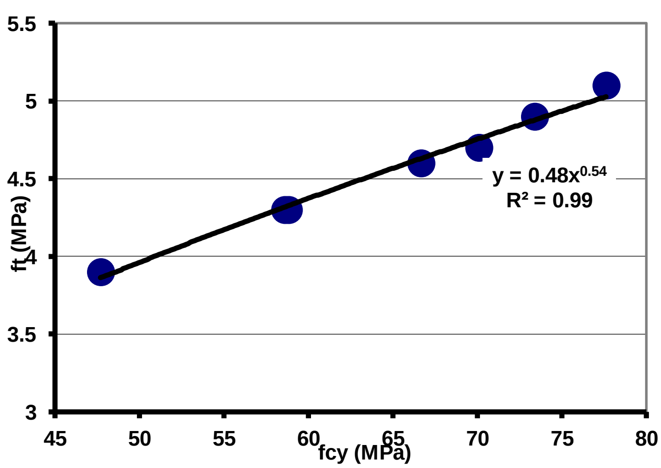


Fig. 5: Relationships between f_t & f_{cy}

3.3 Flexural Strengths

The results of flexural strength tests are listed in Table (12) and plotted in ascending manner in Figure (6). From these results and the high degree of correlation (R = 0.964) between (f_r) and (f_t) for all mixes illustrated in Figure (7), it can be inferred that the changes of the mineral admixtures (type, fineness and dosage) affect the (f_r) in the same manner as (f_t).

Table 12: Results of Flexural Strength (f_r) (MPa)

Mix	f_r
C	8.85
L1	8.25
M1	9.20
D1	9.60
L2	7.43
M2	8.40
D2	8.70

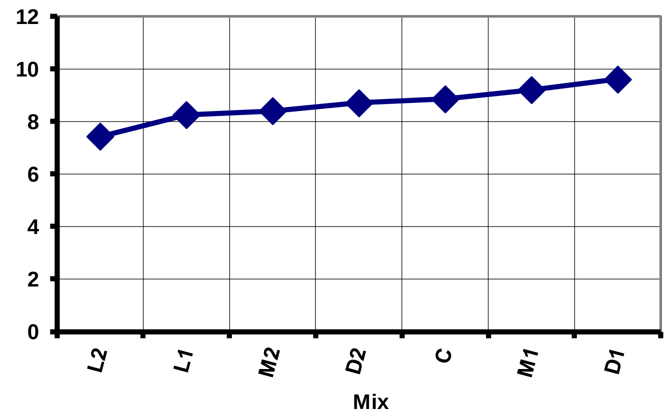


Fig. 6: Flexural Strength (f_r) results

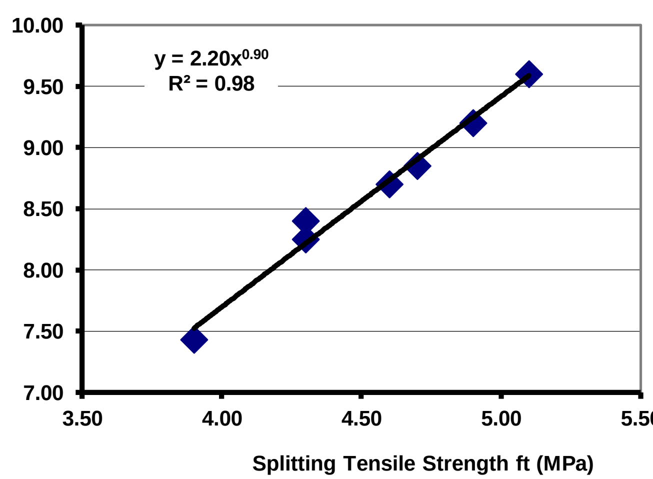


Fig. 7: f_r vs. f_t

The flexural to compressive strength ratios are listed in Table (13) and plotted in Figure (8). From this figure, the following equation is derived:

$$f_r = 1.11 f_{cu}^{0.50}$$

In comparison with the following relationship stated by ACI 318M-14 [13], the SCCs relationship seems to be somewhat close.

$$f_r = 0.7 f_c^{0.50}$$

Table 13: Ratios of (f_r) to (f_{cu})

Mix	f_r / f_{cu}
C	11.80%
L1	13.10%
M1	11.50%
D1	11.29%
L2	14.29%
M2	12.92%
D2	12.08%

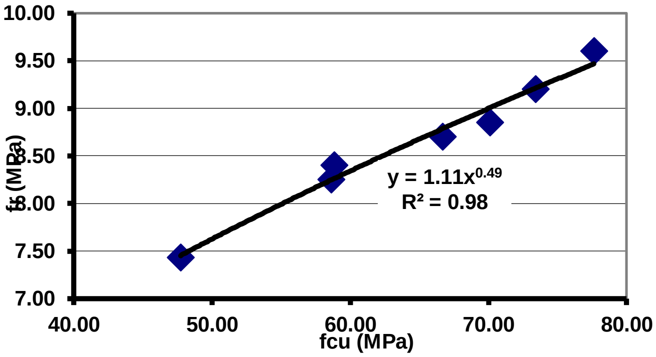


Fig. 8: f_r vs. f_{cu}

3.4 Static Modulus of Elasticity

Table (14) gives the static modulus of elasticity in compression for the mixes. The table also shows the $E/(f_{cy})^{0.5}$ ratios and their deviations (as percentages) from the value (4.7) stated by ACI-318-08 [10]. The (E_c) values are plotted in Figure (9) in ascending manner. From the table and the figure mentioned above, it becomes clear that the values of (E_c) are affected by the mineral admixtures changes (type, fineness and dosages), but the most significant effect is the compressive strength of each mix. The results indicate also that the $E/(f_{cy})^{0.5}$ ratios are slightly lower than the value of ACI-318 Code. The percentages of deviation are lower than (20%). Thus, it can be said that the static elastic modulus of all mixes is within the limits of the ACI-318 Code stated above.

Table 14: Modulus of Elasticity (E_c) (GPa)

Mix	E_c (GPa)	$E/(f_{cy})^{0.5}$	Deviation
C	36.99	4.42	- 5.96%
L1	33.45	4.37	- 7.02%
M1	37.05	4.32	- 8.09%
D1	38.23	4.34	- 7.66%
L2	29.99	4.34	- 7.66%
M2	32.87	4.29	- 8.72%
D2	35.25	4.32	- 8.09%

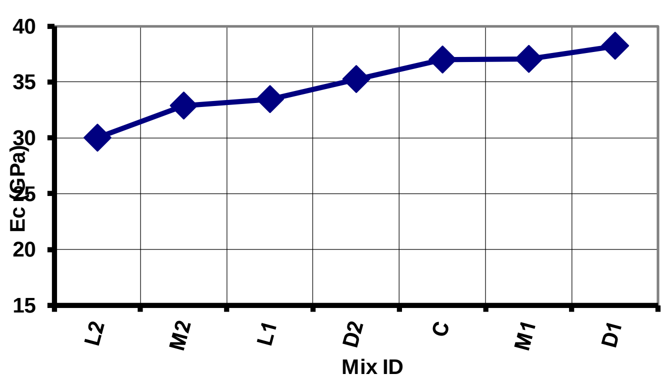


Fig. 9: Static Modulus of Elasticity (E_c) Results

The following empirical relationships between the f_{cy} and E_c for mixes are calculated and plotted in Figure (10). Also, this figure makes comparison between the calculated relationships and two other relationships, the first one is of the ACI-318-08 [10] relationship, and the second is stated by Neville [7] for high performance concretes. The units of E for all equations are in (GPa), and the values of (f_{cy}) from Table (8) are used in the calculations. It is very clear that the estimated relationships are close to those equations from literature.

$$E_c = 4.21 f_{cy}^{\ 0.5} \quad \text{[for SCC mixes]}$$

$$E_c = 4.7 f_c^{\ 0.5} \quad \text{[ACI-318 Code [10] relationship]}$$

$$E_c = 3.32 f_c^{\ 0.5} + 6.9 \quad \text{[Neville [7] relationship]}$$

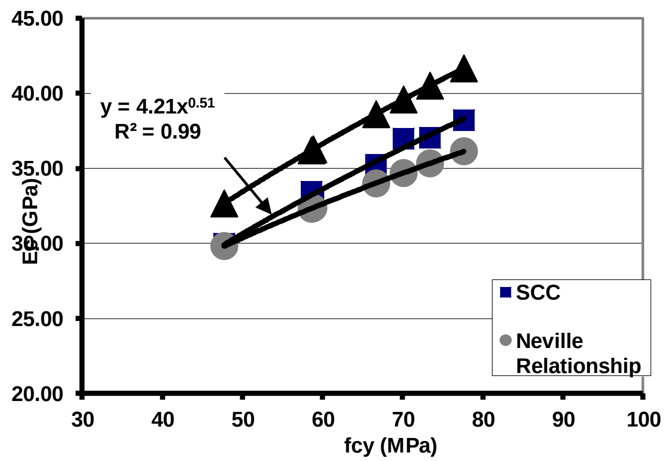


Fig. 10: E_c vs. f_{cy}

4. Non Destructive Tests

4.1 Ultrasonic Pulse Velocity

Table (15) shows the results of ultrasonic pulse velocity measurements gained from testing the mixes with ages of 1, 7, 28 and 90days. It clearly appears that the ultrasonic pulse velocity value increases with age. This is attributed mainly to the increment in the density of the specimen with age and the reduction in points of discontinuity.

Table 15: Results of Ultrasonic Pulse Velocity Tests (V) (km/sec.)

Mix	Ultrasonic Pulse Velocity Results (km/sec.) with Ages			
	1d	7d	28d	90d
C	4.25	4.73	5.04	5.15
L1	4.26	4.60	5.02	5.14
M1	4.22	4.65	5.07	5.32
D1	4.35	4.76	5.12	5.38
L2	4.20	4.45	4.74	4.96
M2	4.05	4.55	4.90	5.17
D2	4.30	4.59	5.00	5.24

Figure (11) shows the results and makes a comparison between them. The replacement of cement by different percentages of the mineral admixtures affects the results in all ages. These effects are not similar and vary according to the type and fineness of the mineral admixture as well as the age of the specimen. At 1 day age in set 2, the results are close to the results of set 1, except for mix D1 which is significantly more. This behavior refers to the very small grain size of LSP, HRM and GDC. These very small grains fill the voids in the skeleton of the concrete and reduce the points of discontinuity. The low (V) of mix M1 at this age can be explained by the high dosage of superplasticizer which delays the setting time of the specimen compared with the others. At 7 days, all the results of mixes in set 2 become less than those for Mix C except for Mix D1. This high (V) of mix C refers to the excess cement content in Mix C compared with the other mixes. The very fine GDC is expected to have a reasonable content of un-hydrated cement particles which can affect the results of the mixes that employ GDC in their formation. Further researches are needed to investigate the chemical behavior of this material. At 28 and 90 days ages, the significant pozzolanic activities of HRM and GDC have great effects on the results. The little improvement of the L1 result refers to a small activity of LSP.

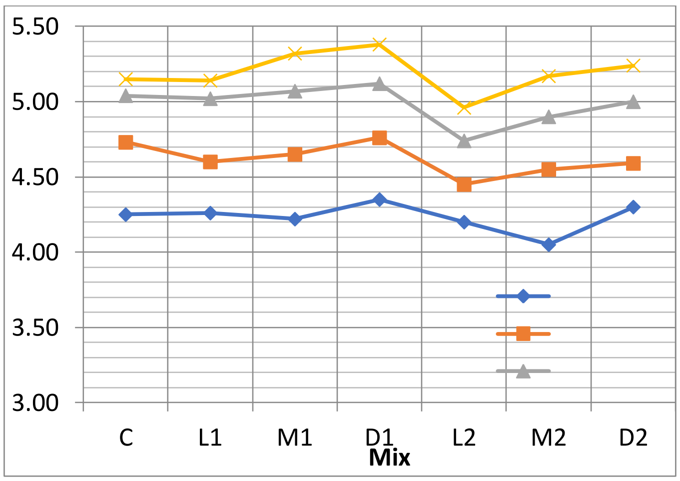


Fig. 11: V results of SCC mixes

The relationship between the ultrasonic pulse velocity (V) and fcy of all mixes is plotted and calculated in Figure (12). The relationship between (Ec) and (V) for the specimens at 28 days age is plotted and calculated in Figure (13). The degrees of correlation for these two figures are (R = 0.97) and (R = 0.89) respectively. It is clear that the ultrasonic pulse velocity increases with the increase of compressive strengths and the modulus of elasticity for all mixes.

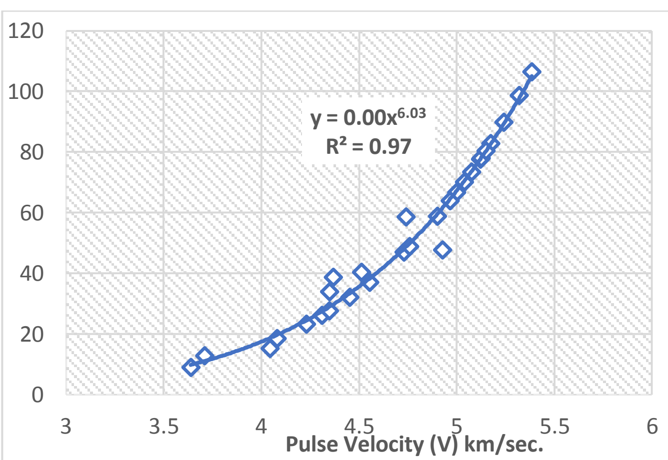


Fig. 12: f_{cy} vs. V

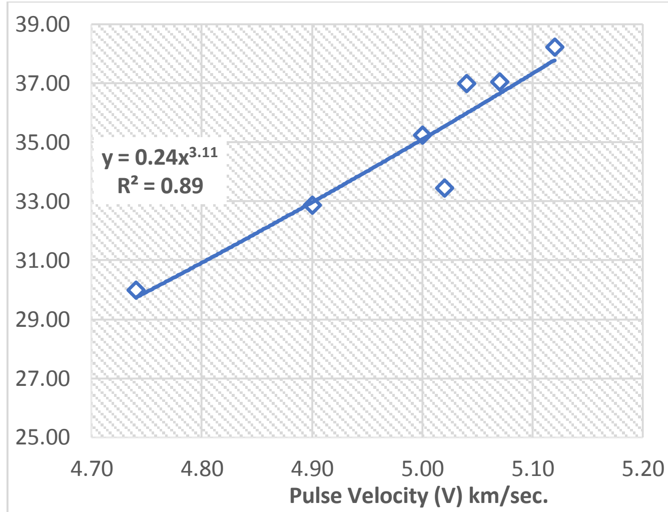


Fig. 13: E_c vs. V

4.2 Dynamic Elastic Modulus

The dynamic elastic modulus is used primarily to evaluate soundness of concrete in durability tests; it is more appropriate value to use when the concrete to be used in structures is subjected to dynamic loading (i.e impact or earthquake) (Mindess and Young (1981) [14]). Table (16) shows the values of dynamic elastic modulus gained from testing the mixes with ages of 1, 7, 28 and 90 days. It clearly appears that the dynamic elastic modulus values increase with age.

Table 16: Dynamic Elastic Modulus (E_d) Values in (GPa)

Mix ID	E_d (GPa) with Ages			
	1d	7d	28d	90d
C	32.29	38.32	42.48	44.01
L1	32.25	36.51	42.00	43.65
M1	31.93	37.33	42.85	46.25
D1	33.42	38.62	43.43	47.04
L2	31.77	34.85	38.57	41.46
M2	30.18	36.31	40.90	44.51
D2	33.12	36.76	42.16	45.42

Figure (14) compares between the values of the (E_d) and (E_c) at 28 days age. Neville [10] stated that, the difference between the dynamic modulus of elasticity of concrete and the static modulus of elasticity of concrete is due to the fact that the heterogeneity of concrete affects the two moduli in different ways. The results of the studied mixes agree with this statement.

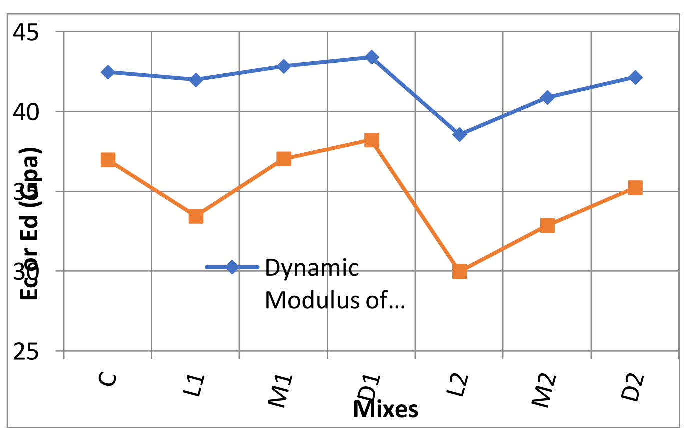


Fig. 14: E_d & E_c values at 28 days age

Mehta 1986 [15] reported that, the dynamic modulus of elasticity is generally 20, 30, and 40 % higher than the static modulus of elasticity for high, medium, and low strength concrete respectively. The ratios of (E_d) to (E_c) at 28 days age for all mixes are listed in Table (17). The range of ratios is 13.6% to 28.6%. This means that the gained concretes have high strength level [16].

Table 17: Ratios of (E_d) to (E_c)

Mix	(E_d / E_c)%
C	14.84%
L1	25.55%
M1	15.65%
D1	13.61%
L2	28.62%
M2	24.43%
D2	19.61%

Figure (15) shows empirical relationship between E_c and E_d at 28 days age, and compares between this relationship and other two relationships from literature. The first of the literature relationship is stated by the British code for the design of concrete structures CP110:1972 [16], and the second is stated by Neville [10], as the simplest relationship proposed by Lydon and Balendran. The correlation factor of the studied relationship is high (R = 0.91). The best fit line of the relationship of SCC mixes is found to have somewhat close slope to that of the British Code relationship. The relationships [17] are as in the following:

$$E_c = 0.02 E_d^{\,2} \quad \text{[for SCC mixes]}$$

$$E_c = 1.25 E_d - 19 \quad \text{[British Code Relationship]}$$

$$E_c = 0.83 E_d \quad \text{[Lydon and Balendran Relationship]}$$

Another empirical relationship between f_{cy} and E_d is calculated and plotted in Figure (16). The values of E_d increase as the values of f_{cy} increase and the relationship between these two properties is:

$$E_d = 18.25 f_{cy}^{\,0.2} \quad (R = 0.940)$$

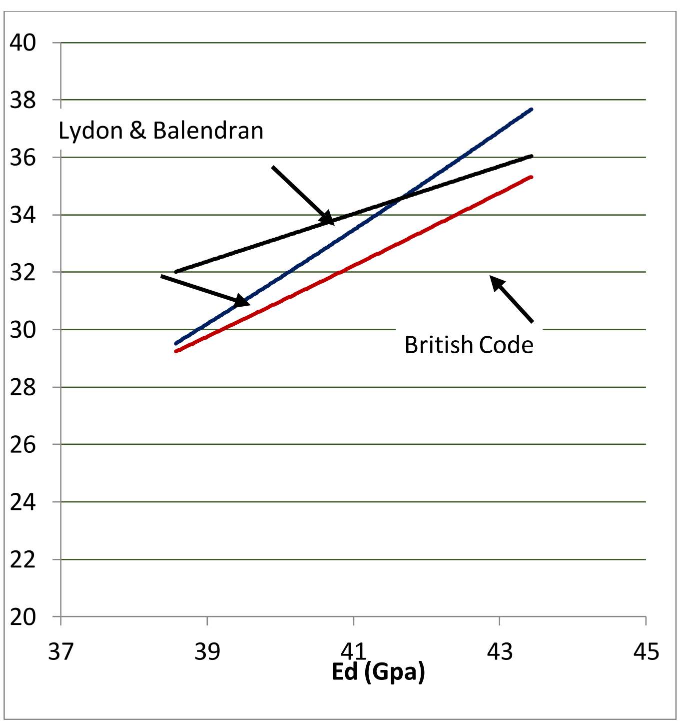


Fig. 15: E_c vs. E_d values (at 28 days age)

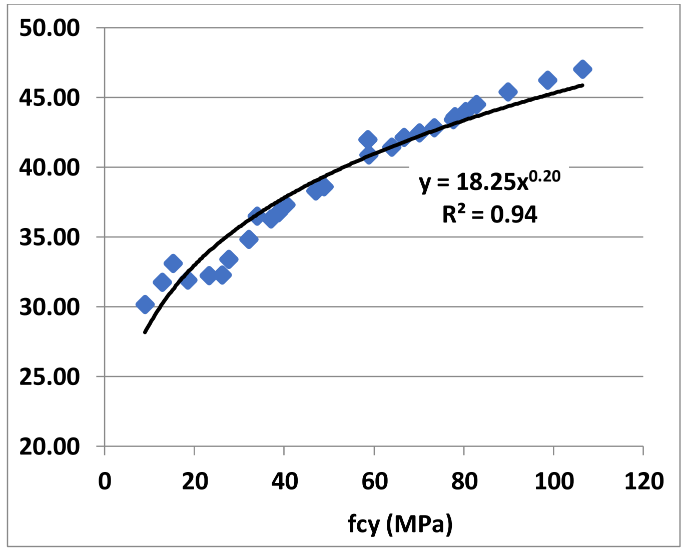


Fig. 16: E_d vs. f_{cy}

4.3 Concrete Density

Densities of the mixes are determined, listed in Table (18). From this table, it is clear that the densities of the studied mixes are in the range of (2472 – 2488). This range [18] is greater than the range of the conventional concrete densities which is 2300 – 2400 [10]. This increment refers to the low water/powder ratios [19] and the employment [20] of the superplasticizer, high powder content and the steel fibers in the mixes [21].

Table 18: Densities (ρ) Values in (kg/m^3)

Mix	ρ (kg/m^3)
C	2472
L1	2459
M1	2470
D1	2465
L2	2473
M2	2488
D2	2484

5. Conclusion

It has been verified that by using the slumpflow and L-box tests, SCC (produced by using locally available materials) achieves consistency and self-compactability under its own weight, without any external vibration or compaction.

Due to the excellent workability, consistency, and self-compactability, studied mixes show high compressive, tensile and flexural strengths with the ranges (48-85) MPa, (4.3-5.1) MPa, and (7.4-9.6) MPa respectively.

The addition of the mineral admixtures with different ratios as a replacement for the weight of cement, significantly affects the strengths of the mixes in all ages. These effects are not similar and vary according to the type, dosage and fineness of the mineral admixture in each mix. The gained strengths are in range from medium to high, thus, it can be recommended that from the economical point of view it is more preferable to employ the replacement part of cement with suitable mineral admixture in producing SCC. The best effects on the hardened properties are for GDC which improves fc up to (31.8%), ft up to (8.51%) and fr up to (8.5%). HRM improves fc up to (23.9%), ft up to (4.26%) and fr up to (4%).

The results indicate that the $E/(fc)^{0.5}$ ratio is slightly lower than the value (4.7) recommended by ACI-318 Code for structural calculations, applicable to normal weight concrete.
The ultrasonic pulse velocity and the dynamic modulus of elasticity are differentially affected according to the variables of the mineral admixtures (type, fineness and dosages).
Because of using the special polycarboxylate superplasticizer, mineral admixtures and steel fibers, SCC mixes achieve densities between 2472 and 2488 kg/m3. This range is greater than the range of the conventional concrete densities which is 2300 – 2400.

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