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Mix Design Guidelines for Concrete Produced Using Portland cement Types Manufactured According to Recent Cement Standard Specifications

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Abstract— Recently issued Portland cement specifications allow producing Portland cement with different types, compositions, and grades that differ from those conventionally produced and used before issuing these specifications. Available mix design methods are based on the conventional Portland cement manufactured and used before issuing these specifications. This triggers the need to develop mix design guidelines based on the different types of cement that become available according to the recently issued cement specifications, therefore the current study has been initiated.

In the current study, 156 different concrete mixes were developed, designed, and carried out experimentally in order to develop design guidelines for the concrete mixtures having cements with different types (Ordinary Portland Cement (CEM I) and blended cement with different additions of limestone and slag (CEM II)), different classes regarding the compressive strength (52.5, 42.5, 32.5), different rates of strength gain (Normal (N) and Rapid (R)), and different production factories (sources), having coarse aggregates with different types typically used (gravel and crushed dolomite) and different maximum sizes (10, 20, and 40 mm), and having fine aggregate (sand) with different gradation zones (fine and coarse). In order to establish a water cement ratio - compressive strength relationships, the concrete mixes considered in the current study were divided into groups, each has the same concrete materials with different water cement ratios and the concrete compressive strength was evaluated by testing standard cubes in compression at ages of 3, 7, 28, 56, and 91 days where a total of 2340 standard cubes were tested. In all mixes, the water content needed to achieve the desired consistency (measured by slump test) was estimated following the guidelines given in the British Standard for concrete mix design.

One of the main outputs of the current study was establishing the water cement ratio – compressive strength relationship for concrete mixtures having different types of concrete materials including new cement types and aggregates typically used in concrete. Moreover, it was verified that estimate of the water content needed to achieve the desired consistency for fresh concrete following the guidelines given in the British Standard for concrete mix design can be followed for concrete mixtures incorporating available cements and aggregates. Accordingly, design guidelines for the concrete mixtures; incorporating available concrete materials including new cement types and typically used aggregates; were developed.

Index Terms— Cement grades, Compressive strength, Crushed aggregate, Mix design, Recent cement specifications, Uncrushed aggregate, Water cement ratio-strength relationship, Workability.

1 Introduction

Recently issued cement specifications [1], [2] allowed the use of cements with different types including ordinary Portland cement and blended cements that contains Portland cement and different types of additions such as limestone, slag, pozzolanic materials with different ratios that ranges from 5% to 95% (namely cement types CEM I, CEM II, CEM III, CEM IV, and CEM V). The produced cements have different classes regarding the compressive strength (namely 52.5, 42.5, 32.5) and different rates of strength gain (Normal (N) and Rapid (R)) [1], [2].

Review of the available concrete mix deign methods [3], [4] revealed the need to develop guidelines for mix design of concrete produced using the new cements and available aggregates.

The main objective of the current study is to develop guidelines that can be used to design concrete mixtures having new cement types manufactured according to the recently issued cement standard specifications and available aggregates typically used in producing concrete.

2 Materials and Methods

In the current study, 156 different concrete mixes were developed, designed, and carried out experimentally in order to develop design guidelines for the concrete mixtures having cements with different types (Ordinary Portland Cement (CEM I) and blended cement with different additions of limestone and slag (CEM II)), different classes regarding the compressive strength (32.5, 42.5, and 52.5), different rates of strength gain (Normal (N) and Rapid (R)), and different production factories (sources). A total of 6 different cements were used and covered by different variables investigated in the current study including four Ordinary Portland cements (namely CEM I 32.5 R, CEM I 42.5 N, CEM I 42.5 R, and CEM I 52.5 N) and two blended cements one of them is a blend of Portland cement with limestone (CEM II/ B-L 32.5 N), and the other one is a blend of Portland cement with slag (CEM II/ A-S 42.5 N). Three additional cements; namely two replicates of

CEM I 42.5 N and a replicate of CEM II/ B-L 32.5 N; but from different sources (i.e. different factories) were also used in limited mixes in order to evaluate the effect of the source on the results. Table 1 shows the physical properties of the different cements considered in the current study tested according to the Egyptian Standards methods [5], [6], [7], [8], [9], [10]. Table 2 shows the chemical compositions for two of the cements used in the current study to provide representative data for the typical chemical compositions of the cements used tested according to the Standard test method [11].

Coarse aggregates used includes gravel and crushed dolomite; that are typically used in producing concrete; having different maximum sizes of 10, 20, and 40 mm. The fine aggregate (sand) used had two different grading zones (namely fine and coarse). Tables 3 and 4 shows the physical properties for coarse and fine aggregate used in the current study respectively.

TABLE 1
PHYSICAL PROPERTIES OF DIFFERENT CEMENTS USED IN THE CURRENT STUDY

Cement types	Source	Le Chatelier expansion (mm)	Initial setting time (min)	Final setting time (min)	Fineness by Blaine (m^2/kg)	Compressive strength (MPa)		
						2 days	7 days	28 days
CEM I 32.5 R	1	1	125	170	320	NA	22	41.3
CEM I 42.5 N	1	1	140	185	345	20.5	NA	46.2
CEM I 42.5 R	1	1	140	185	325	21	NA	48.6
CEM I 52.5 N	1	1	140	185	330	23.1	NA	54.7
CEM II/ B-L 32.5 N	1	1	125	170	305	NA	22	40.3
CEM II/ A-S 42.5 N	1	1	135	180	-	19.9	NA	45.3
CEM I 42.5 N	2	1	140	185	-	20.6	NA	46.5
CEM I 42.5 N	3	1	140	185	-	18.9	NA	47.2
CEM II/ B-L 32.5 N	2	1	125	170	-	NA	22	40.6

TABLE 2
CHEMICAL COMPOSITION OF TWO CEMENTS USED IN THE CURRENT STUDY

Oxide	CEM I 32.5 R (1) result %(by mass)	CEM I 42.5 N (1) result %(by mass)
SiO_2	26.32	20.99
Al_2O_3	5.06	4.88
Fe_2O_3	4.09	3.71
CaO	56.47	61.30
MgO	2.28	2.5
So_3	2.23	2.65
LOI	2.93	3.24
Na_2O	0.04	0.51
K_2O	0.19	0.18
Ins.Res.	0.73	0.68

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TABLE 3
PHYSICAL PROPERTIES OF COARSE AGGREGATES USED

Property	Maximum aggregate size (mm)		
	10	20	40
Crushed dolomite			
Specific gravity	2.67	2.67	2.67
Unit weight (t/m^3)	1.61	1.63	1.69
Materials finer than sieve No. 200	1.3%	0.9%	0.7%
Gravel			
Specific gravity	2.7	2.7	2.7
Unit weight (t/m^3)	1.69	1.75	1.81
Materials finer than sieve No. 200	1.6%	0.7%	0.6%

TABLE 4
PHYSICAL PROPERTIES OF FINE AGGREGATE (SAND) USED

Property	Fine graded	Coarse graded
Specific Gravity	2.65	2.6
Unit weight (t/m^3)	1.76	1.66
Materials finer than sieve No. 200	2.8	1.9

In order to establish a water cement ratio - compressive strength relationships, the concrete mixes considered in the current study were divided into groups, each has the same concrete materials with different water cement ratios and the concrete compressive strength was evaluated by testing standard cubes in compression at ages of 3, 7, 28, 56, and 91 days where a total of 2340 standard cubes were tested. In all mixes, the ratio of the sand in all aggregate and the water content needed to achieve the desired consistency (measured by slump test) were estimated following the guidelines given in the British Standard for concrete mix design [4]. Table 5 shows the details of the concrete mixes considered in the current study.

Consistency of fresh concrete was measured experimentally by standard slump test. Casting of concrete compression test specimens was carried out in cast iron 150mm-cube molds and were stripped 24 hours after casting, then the concrete cubes were immersed in standard curing tanks until test time. The compressive strength was determined by testing the concrete cubes in compression using 2,000kN compression testing machine with sensitivity of 5kN. Before testing, the concrete cubes were removed from the curing tanks and left in open air in the laboratory for two hours. The results presented are the average of three cubes.

3 RESULTS AND DISCUSSION

3.1 Consistency of fresh concrete

Slump test was carried out as a measure of fresh concrete for all mixtures considered in the current study using different concrete materials and different free water contents. As mentioned in the previous section, the water content needed to achieve the desired consistency was estimated following the guidelines given in the British Standard and reproduced in Table 6.

TABLE 5
DETAILS OF THE DIFFERENT MIXES CONSIDERED IN THE CURRENT STUDY.

Mix	Cement used		Type of coarse aggregate	NMS*	Grading zone of sand	Cement content	Sand content	Coarse aggregate content	Free water content	Free water cement ratio
	Types	Source		(mm)		(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	
M1:6	1.CEM I 32.5 R, 2.CEM I 42.5N, 3.CEM I 42.5 R, 4.CEM I 52.5N, 5.CEM II /B-L 32.5N 6.CEM II /A-S 42.5N	1	Gravel	10	Coarse	300	810	1120	180	0.60
M7:12					Fine	300	700	1230	180	0.60
M13:18, M19:24, M25:30, M31:36				20	Coarse	500,400, 300,250	610,740, 810, 960	1200, 1100, 1120, 960	160, 180, 180, 195	0.32, 0.45, 0.6, 0.76
M37:42					Fine	300	700	1230	180	0.60
M43:48, M49:54, M55:60, M61:66				40	Coarse	450, 350, 275, 225	500, 640, 740, 380	1410, 1290, 1260, 1120	140, 160, 160, 175	0.31, 0.46, 0.58, 0.78
M67:72					Fine	275	580	1420	160	0.58
M73:78			Crushed dolomite	10	Coarse	350	760	1040	210	0.60
M79:84					Fine	350	630	1170	210	0.60
M85:90, M91:96, M97:102, M103:108				20	Coarse	500, 450, 350,300	590, 650, 760, 900	1140, 1060, 1040, 900	190, 210, 210, 225	0.38, 0.47, 0.60, 0.75
M109:114					Fine	350	630	1170	210	0.60
M115:120, M121:126, M127:132, M133:138				40	Coarse	500, 400, 300, 275	490, 650, 720, 840	1270, 1160, 1170, 1030	175, 190, 190,205	0.35, 0.48, 0.63, 0.75
M139:144					Fine	300	570	1330	190	0.63
M145:147	7.CEM I 42.5N, 8.CEM I 42.5N, 9.CEM II /B-L 32.5N	2	Gravel	20	Coarse	300	810	1120	180	0.60
M148:150				40	Coarse	275	740	1260	160	0.58
M150:153			Crushed dolomite	20	Coarse	350	760	1040	210	0.60
M154:**156**				40	Coarse	300	720	1170	190	0.63

*NMS: nominal maximum aggregate size (mm).

TABLE 6
FREE-WATER CONTENTS (KG/M3) REQUIRED TO GIVE VARIOUS LEVELS OF CONSISTENCY AS MEASURED BY THE SLUMP ACCORDING TO THE BRITISH STANDARD [4]

Slump range (mm)		0–10	10–30	30–60	60–180
Maximum size of coarse aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	crushed	155	175	190	205

Fig. 1 shows the relationship between free water content - slump test results for all mixes that contains different concrete materials including different cements and aggregates together with values of the British standard given in Table 6. The test results shown in Fig. 1 clearly verify that the estimate of free water content needed to achieve a desired slump according to the British standard can be used for concrete mixtures incorporating different types of available concrete materials. It is concluded that the water contents estimate needed to achieve different levels of slump according to the British standard (Table 6) can be used for concrete mixtures having typically used concrete materials as considered in the current study. It is to be noted that the water content needed to achieve certain slump increases with the decrease in maximum size of the coarse aggregate. Also the concrete mixes having gravel (uncrushed) coarse aggregate need less water content to attain the slump compared to mixes with crushed dolomite. Based on the results presented in Fig. 1 and Table 6, Fig. 2 is developed for use in estimating the free water content needed to achieve the slump for concrete mixes having coarse aggregates of gravel (uncrushed) and crushed dolomite respectively.

3.2 Compressive strength

In order to establish a water cement ratio - compressive strength relationships for concrete produced using concrete materials including cements produced according to the recently issued cement standard specifications and typically used aggregates, all concrete mixes considered in the current study were divided into groups, each has the same concrete materials with different water cement ratios. The concrete compression test results were used to establish the water cement ratio – compressive strength (w/c-fc) relationships for different concrete materials considered in the current research at ages of 3, 7, 28, 56, and 91 days. All established (w/c-fc) relationships are published elsewhere [12]. Due to space limitations, only (w/c-fc) relationship at 28 day age is shown in Figs. 3 and 4 for concrete having coarse aggregates of gravel (uncrushed aggregate) and crushed dolomite (crushed aggregate) respectively and different cements.

It is clearly demonstrated in Figs 3 and 4 that the effect of changing the maximum size of coarse aggregate and grading zone of the sand on (w/c-fc) relationship is marginal for concretes having the same type of coarse aggregate. It is therefore concluded that, for concretes having the same type of coarse aggregate, the (w/c-fc) relationship is independent of the maximum size of coarse aggregate and grading zone of sand used, i.e one curve for (w/c-fc) relationship is applicable to all aggregates having different maximum sizes for coarse aggregate or different grading zones for fine aggregate. On the other hand, the results shown in Figs. 3 and 4 confirm that the type of coarse aggregate significantly affects the (w/c-fc) relationship where, for the same w/c ratio, the concrete having uncrushed aggregate (gravel) has considerably lower compressive strength compared to that with crushed aggregate (dolomite). This triggers the need to develop separate curves for the (w/c-fc) relationship for cases of concrete with uncrushed and crushed coarse aggregate.

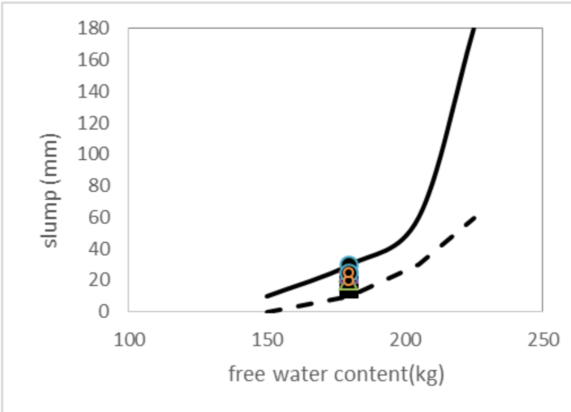
In order to evaluate the effect of type of cement and coarse aggregate used on the (w/c-fc) relationship at 28 days, Fig. 5 is constructed showing (w/c-fc) curves for different cements considered in the current study splitted into two groups one for the concrete having gravel (uncrushed) as coarse aggregate while the other one for concrete having dolomite (crushed) as coarse aggregate. The data shown in Table 1 and Fig. 5 clearly indicate that the (w/c-fc) relationship at 28 days for concrete having the different cements considered the in the current study is mainly dependent on the cement compressive strength at 28 days regardless the cement composition (CEM I or CEM II) nor the rate of strength gain (Normal (N) or Rapid (R)) where the (w/c-fc) curves shown in Fig. 5 are arranged in descending order from the top curve for CEM I 52.5 N that had the highest cement compressive strength at 28 days of 54.7 MPa (see Table 1) down to the bottom curve for CEM II 32.5 that had the lowest cement compressive strength at 28 days of 40.3 MPa (shown in Table 1). Accordingly, for the sake of developing (w/c-fc) curves to be used in the concrete mix design, it is proposed to have one curve representing the (w/c-fc) relationship for each cement class (i.e. three curves for cement with classes 32.5, 42.5, and 52.5). Therefore, the six curves shown in Fig. 5 representing the different cements used in the current study are reduced into only three curves, namely CEM II/ B-L 32.5 N curve (lower bound for cement classes 32.5) representing cement class 32.5, CEM II/ A-S 42.5 N curve (lower bound for cement classes 42.5) representing cement class 42.5, and CEM I 52.5 N curve representing cement class 52.5 as shown in Fig. 6.

In order to ease the use of (w/c-fc) relationships proposed in Fig. 6, a trial was made to change the curved shape of the relationship to a straight line through plotting the compressive strength (fc) against the logarithm (Log) of w/c as shown in Fig. 7. The reproduced (log w/c -fc) relationships are straight lines that can be expressed by straight line equations shown in Fig. 7.

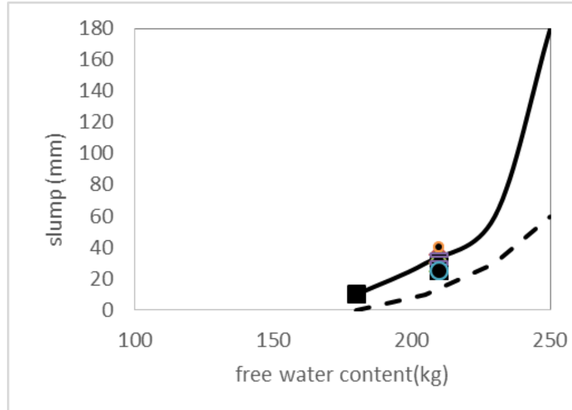
4 Conclusions

Based on the results and analysis presented, the following conclusions may be drawn:

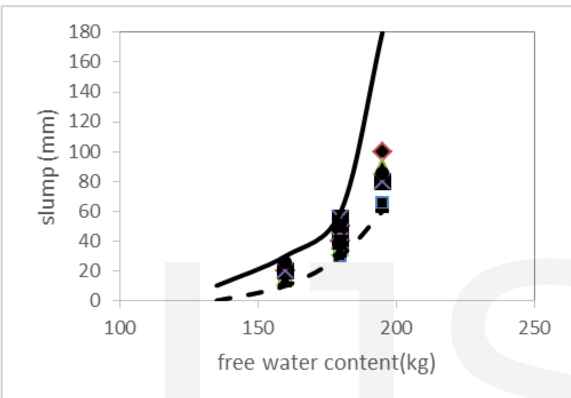
- The water content needed to achieve certain slump increases with the decrease in maximum size of the coarse aggregate. Also the concrete mixes having gravel (uncrushed) coarse aggregate need less water content to attain the slump compared to mixes with crushed dolomite.
- The water contents estimate needed to achieve different levels of slump as recommended by the British standard [4] can be used for concrete mixtures having typically used concrete materials as considered in the current study. Accordingly, Fig. 2 is developed for use in estimating the free water content needed to achieve the slump for concrete mixes having coarse aggregates of gravel (uncrushed) and crushed dolomite respectively.
- For concretes having the same type of coarse aggregate, the effect of changing the maximum size of coarse aggregate and grading zone of the sand on the (w/c-fc) relationship is marginal. It is therefore concluded that (w/c-fc) relationship is independent of the maximum size of coarse aggregate and grading zone of sand used, i.e one curve for (w/c-fc) relationship is applicable to all aggregates having different maximum sizes for coarse aggregate or different grading zones for fine aggregate.
- The results confirm that the type of coarse aggregate significantly affects the (w/c-fc) relationship where, for the same w/c ratio, the concrete having uncrushed aggregate (gravel) has considerably lower compressive strength compared to that with crushed aggregate (dolomite).
- The results indicate that the (w/c-fc) relationship at 28 days for concrete having the different cements considered the in the current study is mainly dependent on the cement compressive strength at 28 days regardless the cement composition (CEM I or CEM II) nor the rate of strength gain (Normal (N) or Rapid (R)). Accordingly, for the sake of developing (w/c-fc) curves to be used in the concrete mix design, it is proposed to have one curve representing the (w/c-fc) relationship for each cement class (i.e. three curves for cement with classes 32.5, 42.5, and 52.5). Fig. 6 shows the proposed (w/c-fc) relationships for the cement classes 32.5, 42.5 and 52.5.
- The results shown in the current study can be used as a base for the design mix of concrete having different cement types produced according to the recently issued cement standard specifications [1],[2] and available aggregates typically used in concrete (sand, gravel and crushed dolomite) where Fig. 2 can be used to estimate the water content needed to achieve the desired slump and Figs. 6 and 7 can be used to estimate the water cement ratio needed to achieve the target compressive strength.



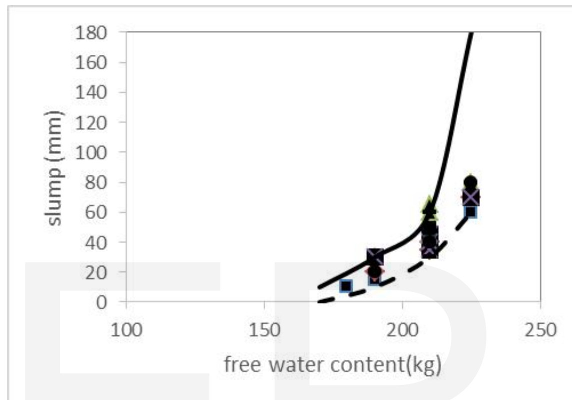
a) Uncrushed coarse aggregate with NMS 10



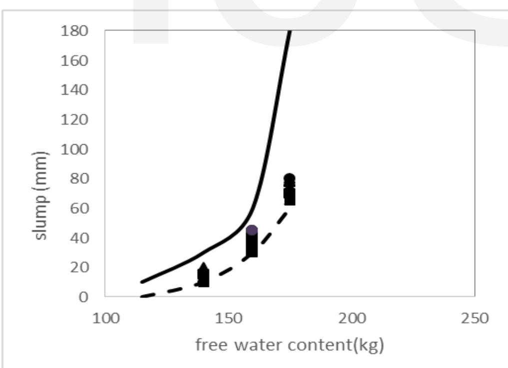
b) Crushed coarse aggregate with NMS 10



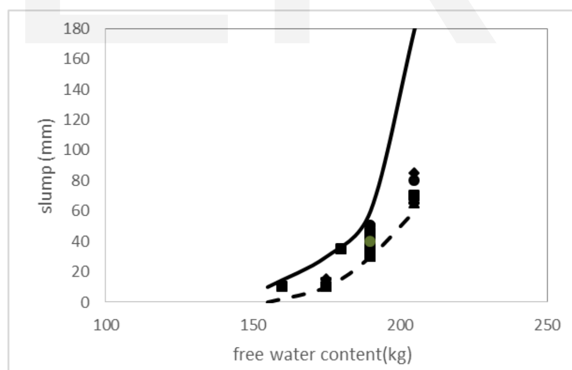
c) Uncrushed coarse aggregate with NMS 20



d) Crushed coarse aggregate with NMS 20



e) Uncrushed coarse aggregate with NMS 40



f) Crushed coarse aggregate with NMS 40

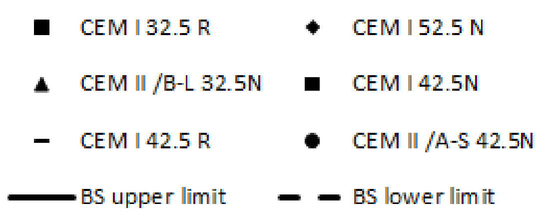
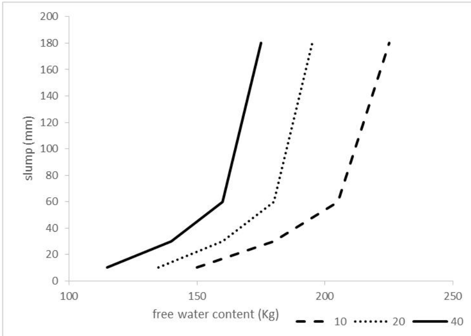
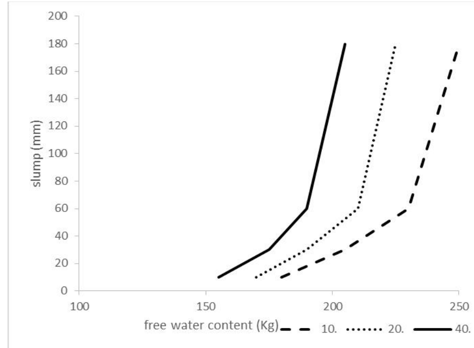


Fig. 1. Relationship between water content and slump for all concrete mixtures considered in the current study

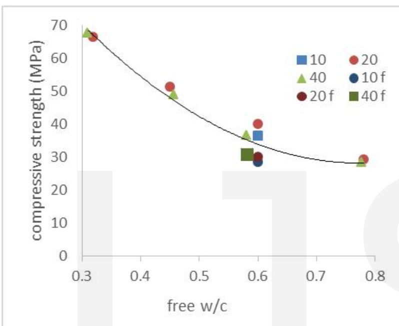


a) Gravel

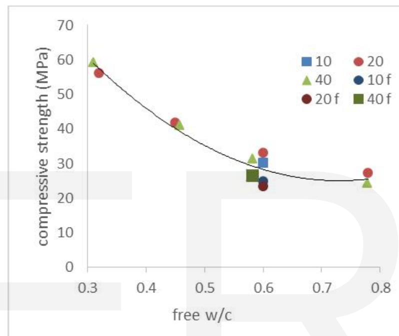


b) Uncrushed dolomite

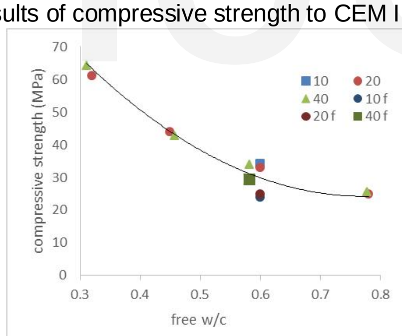
Fig. 2. Estimate for free water content needed to achieve the desired slump for concrete mixes having - a) Grvel b) crushed dolomite - as coarse aggregate with maximum aggregate sizes of 10, 20 and 40 mm.



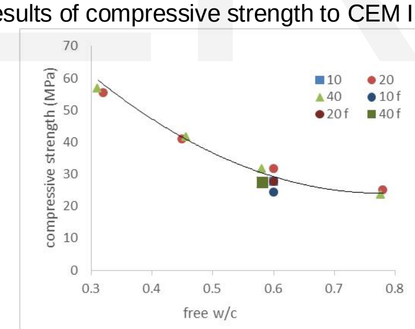
a) Results of compressive strength to CEM I 52.5 N.



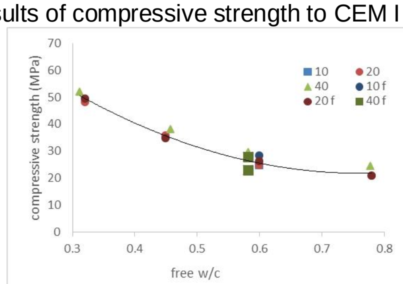
b) Results of compressive strength to CEM I 42.5 N.



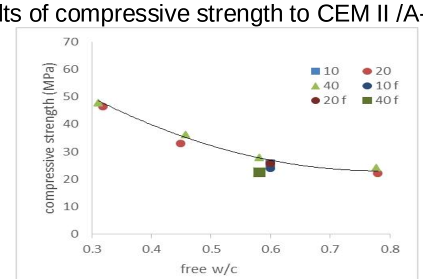
c) Results of compressive strength to CEM I 42.5 R.



d) Results of compressive strength to CEM II /A-S 42.5N.

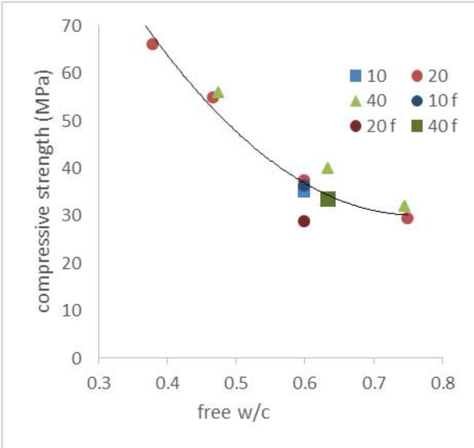


e) Results of compressive strength to CEM I 32.5 R.

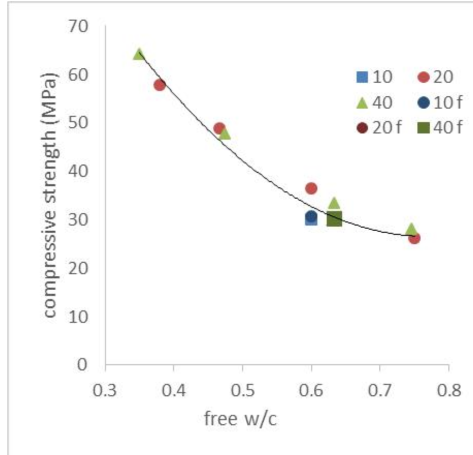


f) Results of compressive strength to CEM II /B-L 32.5N.

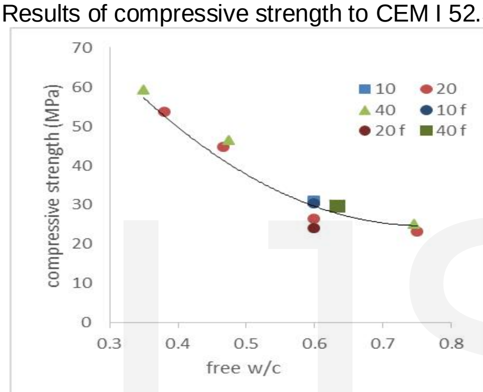
Fig. 3. Water cement ratio – compressive strength (w/c-fc) relationships at 28 day age for concrete having coarse aggregate of gravel and different cement types



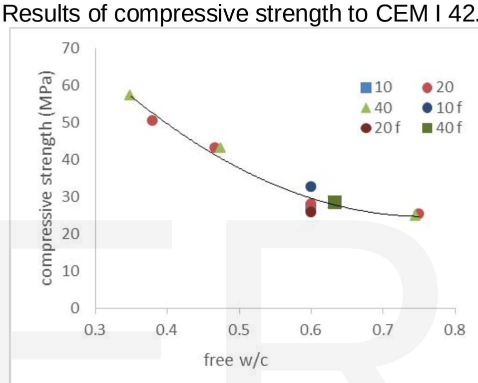
a) Results of compressive strength to CEM I 52.5 N.



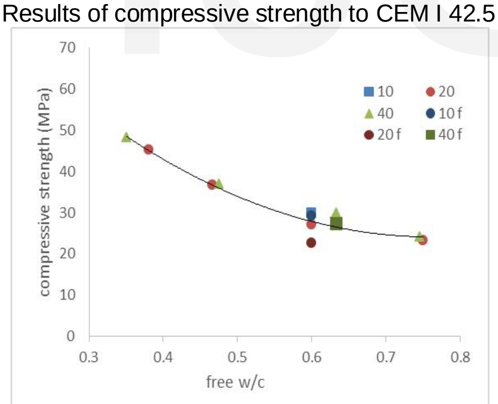
b) Results of compressive strength to CEM I 42.5 N.



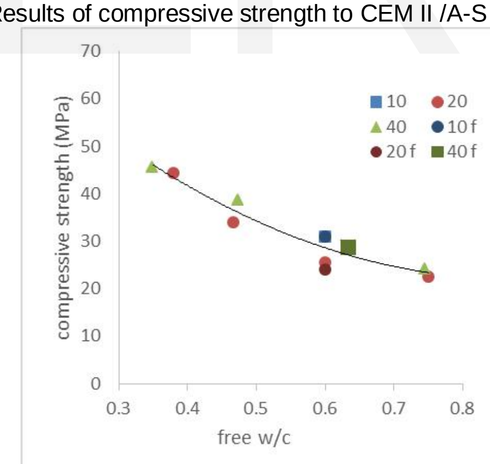
c) Results of compressive strength to CEM I 42.5 R.



d) Results of compressive strength to CEM II /A-S 42.5N.

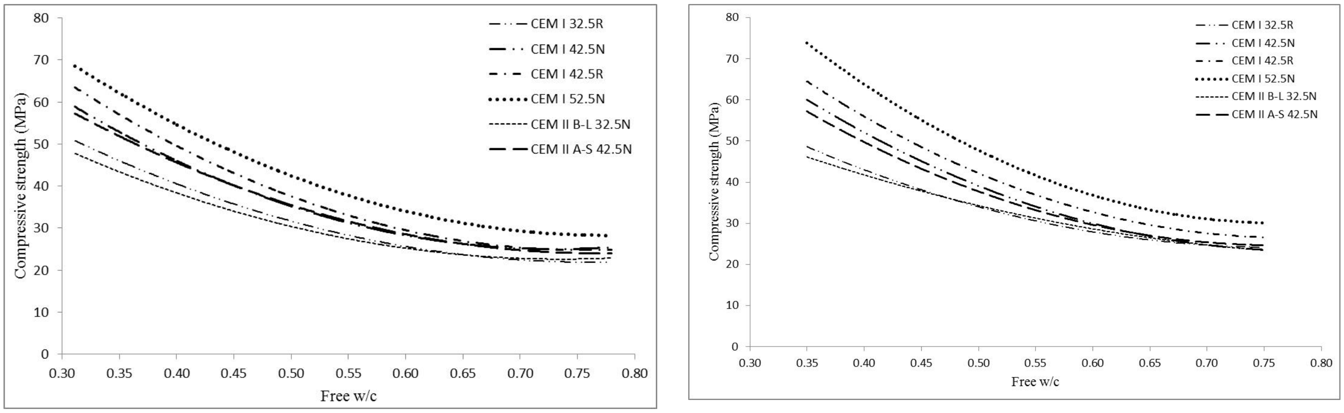


e) Results of compressive strength to CEM I 32.5 R.



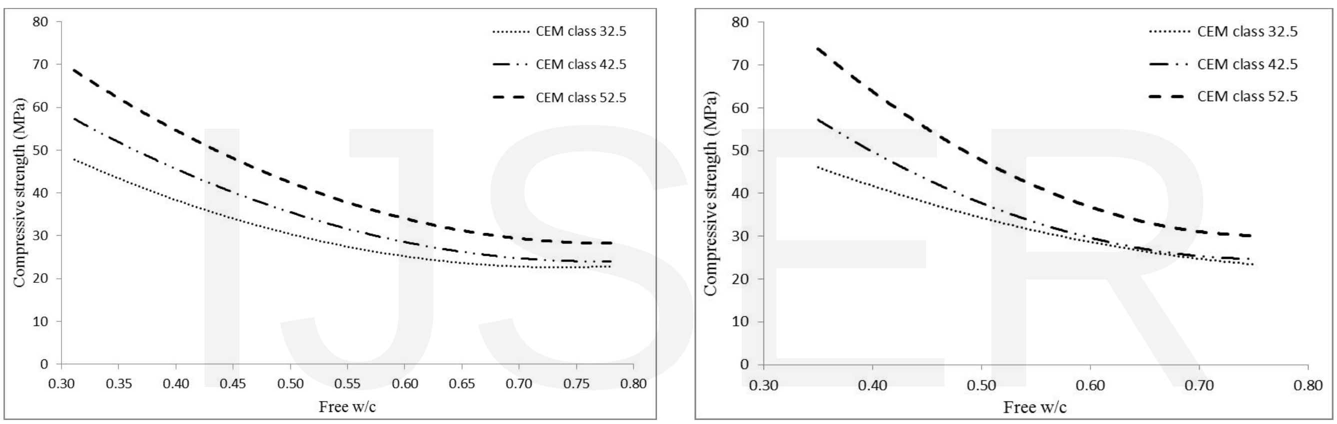
f) Results of compressive strength to CEM II /B-L 32.5N.

Fig. 4. Water cement ratio – compressive strength (w/c-fc) relationships at 28 day age for concrete having coarse aggregate of crushed dolomite and different cement types



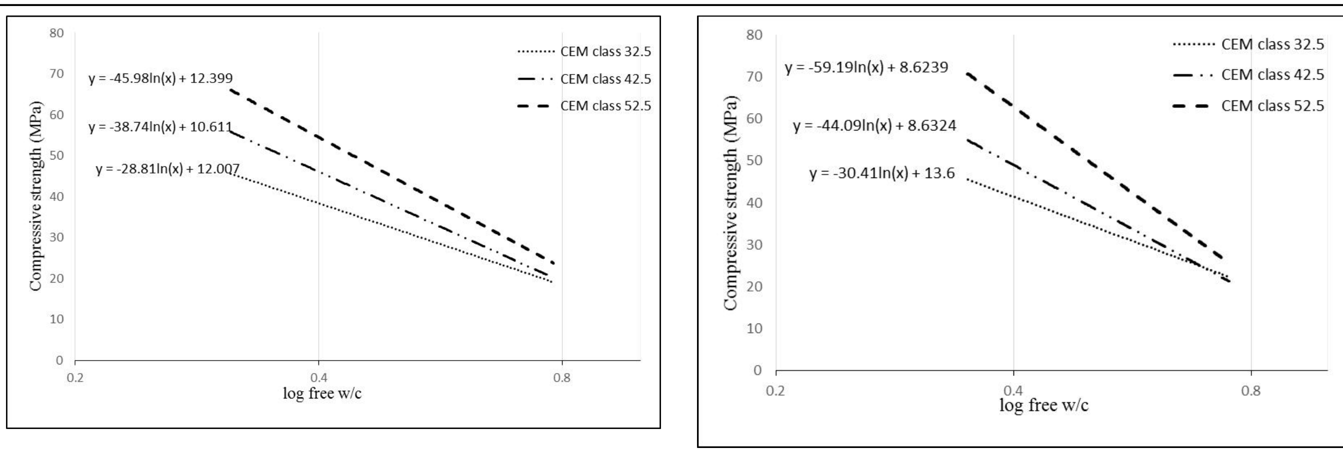
a) Gravel b) Uncrushed dolomite

Fig. 5. Comparison for water cement ratio – compressive strength (w/c-fc) relationships at 28 day age for concrete having different types of cements and coarse aggregates of (a) gravel (uncrushed) and (b) crushed dolomite



a) Gravel b) Uncrushed dolomite

Fig. 6. Proposed water cement ratio – compressive strength (w/c-fc) relationships at 28 day age for concrete having cement classes 32.5, 42.5, and 52.5 and coarse aggregates of (a) gravel (uncrushed) and (b) crushed dolomite



a) Gravel b) Uncrushed dolomite

Fig. 7. Proposed log (water cement ratio) – compressive strength (Log(w/c) - fc) relationships at 28 day age for concrete having cement classes 32.5, 42.5, and 52.5 and coarse aggregates of (a) gravel (uncrushed) and (b) crushed dolomite

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