A COMPARISON BETWEEN AMERICAN AND BRITISH METHODS OF MIX DESIGN WITH SUGGESTIONS FOR IMPROVEMENT

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Abstract

This paper presents an analytical calculation and experimental investigation to evaluate the American and British methods usually used for mix design of normal concrete. Six concrete mixes with different target of mean strength were design using crushed and uncrushed aggregates. A reliable approach has been suggested to calculate the mix proportions. In order to validate the former approach, an experimental programme was running to measure the workability aspect and compressive strength of three selected concrete mixes designed for strength levels of 21.5 MPa, 27.5 MPa and 36.5 MPa at different sample ages using 108 cubes.

The results obtained showed notable differences between the approaches of American and British methods adopted to calculate the mix proportions. There was no indication have found in the American method to distinct between design the concrete mix containing crushed aggregate and that of uncrushed aggregate. The procedure followed in British method produced concrete mix with higher strength than that designed according to American method. The experimental results of compressive strength and workability showed close agreement with the suggested approach for calculation the mix proportions.

Keywords: mix design, compressive strength, workability, aggregate properties.

الخلاصة

يعرض هذا البحث حسابات تحليلية و تحريات مختبرية لتقييم الطريقتين الامريكية والبريطانية المعتمدة لتصميم الخلطة الخرسانية الاعتيادية. صُممت ستة خلطات خرسانية ذات مديات مختلفة من المقاومة بإستخدام الحصى المكسر بجانب وغير المكسر بجانب اخر. تم اقتراح إسلوب مقبول للحصول على نسب الخليط عند تصميم الخلطة بالطريقتين. ولاجل التاكد من صلاحية هذا الاسلوب تم اجراء برنامج عملي لقياس قابلية التشغيل ومقاومة الانضغاط لثلاث خلطات مختارة وبمقاومات تصميمة مقدارها ٢١.٥ ميكاباسكال،٢٧.٥ ميكاباسكال و ٣٦.٥ ميكاباسكال وبأعمار مختلفة باستخدام ١٠٨ مكعب.

أظهرت النتائج المستحصلة اختلاف ملحوظ بين المنهج المتبع في الطريقتين الامريكية والبريطانية لتحديد نسب الخليط. فالطريقة الامريكية لم تميز في التصميم بين طبيعة الركام المستخدم في الخرسانة سواء كان مكسر او غير مكسر. اما المنهج المتبع في الطريقة البريطانية فيميز بين طبيعة الركام المستخدم وينتج خرسانة ذات مقاومة انضغاط اعلى منها في الطريقة الامريكية. نتائج الفحوصات اظهرت توافق كبير بينها وبين المنهج المقترح لتعديل الحسابات الخاصة بتصميم الخلطة الخرسانية.

1. Introduction

Concrete is the most consumption material that will keep its forefront in the construction market far into the future. The annual concrete demand in the world reached about 1.8 billion tones in 2014 [1]. This massive utilize requires continuous improving the overall properties, methods of production and diversifying the sources of raw materials [2, 3].
As the concrete is a composite material consisting binder medium and aggregate phases, so improving of its properties should come up based upon these phases. Nevertheless, the conflicting behaviour of concrete components restricts most of the improving efforts, where the aggregate phase is a function of its mineralogy whilst the binder medium is a function of time [4].
In general, aggregate takes up 75% of the total volume of concrete. Thus, concrete properties are highly affected by physical properties of its aggregate such as size and shape of particles, surface texture and grading of the whole aggregate sample. The aggregate shape plays essential role in determination the workability of concrete due to the differences in surface area caused by different shapes. On this basis, the available cement paste should be enough to coat the aggregate surfaces and provided lubrication. Most of the fresh concrete properties, the interaction bond between aggregate and cement paste of the hardened concrete as well as the energy disbursed in compaction of concrete are direct effect of aggregate surface texture. A well graded aggregate can minimize the required quantity of cement paste by a significant amount [5]. To achieve the optimized grading, there are several methods, such as, grading curve, individual percent retained curve and combined fineness modulus (fineness modulus of total aggregate) [6].
Obviously, the cement paste is responsible for tying the aggregate particles together and providing the mechanical strength of concrete. This task normally depends upon the composition of cement and results of hydration process with time [4, 7].
In order to produce a concrete with high quality, a mix design usually follows up to identify the suitable quantities of raw materials (cement, sand, gravel and water) which satisfy the criteria of strength, workability and durability. The raw materials used in concrete vary in a number of aspects and their properties are difficult to be adjusted truly quantitatively. Therefore, different strategies were suggested to select the suitable mix proportion of concrete [6, 8]. The elementary technique of surface/mix suitability factor (MSF) was followed to give a global view for the percentages of the materials used. Little information required for this technique such as grading of sand, a verbal description of the appearance of the coarse aggregate and where the concrete to be used [6]. More recent techniques which have wide application in the field of concrete constructions are the American and British methods for mix design. These methods take in consideration the status of raw materials and different requirements for the concrete mix to be designed. In general, the latter methods have been derived based upon statistical concepts. They accept that concrete strength tends to be a normally distributed variable and considered in terms of mean strength and standard deviation rather than an absolute limit [9, 10]. However, assessment the former methods is needed especially for the locally available materials in Iraq.

In this study a comparison between the American and British methods of mix design has been made for wide range of concrete strength taken in consideration the variation of coarse aggregate used. The evaluation of these methods was also investigated throughout an experimental programme for selected strength targets and modification to site local materials have been suggested.

2. Mix design of concrete

2.1 Methodology and procedure

The determination of mix proportion for a normal concrete using ordinary Portland cement was adopted in this study. This type of concrete has a wide application and represents the standardize case. The procedures presented by A M Neville [9] and D C Teychenné et al. [10] were followed for American and British methods respectively. Six concrete mixes with strength level ranging from 15 MPa to 40 MPa have been designed. For both methods, the data used were: the value of slump was in the range of (75-100) mm; the concrete was assumed to be protected from the sulfate attacked and other aggressive solutions. The maximum aggregate size was 37.5 mm which is suitable for use with the light reinforcement and the coarse aggregate was in two states: crashed and uncrushed. The properties of sand were similar to that presented in the experimental programme, Section 3.
Based upon the former data, the determination of mix proportion according to the American method required the following steps: 1.estimation the mixing water and air content from Table (1); 2.selection the W/C ratio from Table (2); 3.calculation the cement content; 4.estimation the content of coarse aggregate from Table (3); 5.calculation the content of fine aggregate; 6. adjustion the field moisture for aggregate.

Table 1: Approximate amounts of mixing water and air content requirements for Non-Air entrained concrete [9]

Slump (mm)	Water content (kg/m^3)						
	Maximum Aggregate size (mm)						
	9.5	12.5	19	25	37.5	50	75
25-50	207	199	190	179	166	154	130
75-100	228	216	205	193	181	169	145
150-175	243	228	216	202	190	178	160
Entrapped Air (%)	3	2.5	2	1.5	1	0.5	0.3

Table 2: Relationship between the “Water/Cement” ratio and compressive strength of concrete [9]

Compressive strength at 28 days (MPa)	" Water/Cement " Ratio (by weight)	
	Non-air-entrained concrete	Air-entrained concrete
50	0.42	---
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

Table 3: Volume of coarse Aggregate per unit volume of concrete [9]

Maximum size of aggregate (mm)	Volume of dry-rodded coarse aggregate per unit volume of concrete

	Fineness modulus of fine Aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19.0	0.66	0.64	0.62	0.60
25.0	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50.0	0.78	0.76	0.74	0.72
75.0	0.82	0.80	0.78	0.76

In terms of the British method, the determination of mix proportions consist the following procedure: 1.selection the preliminary strength based on the used cement strength class as in Table 4; 2.slection the W/C ratio from Figure 1; 3.calculation the mixing water depending on the maximum size of aggregate from Table 5; 4. calculation the cement content; 5. determination the density of concrete from Figure 2; 6. estimation the ratio of fine aggregate using Figure 3; 7. calculation the quantity of fine and coarse aggregate; 8. adjustion the field moisture for aggregate.

Table 4: Approximate compressive strengths (N/mm^2) of concrete mixes made with a free-water/cement ratio of 0.5 [10].

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm^2)			
		Age (days)			
		3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

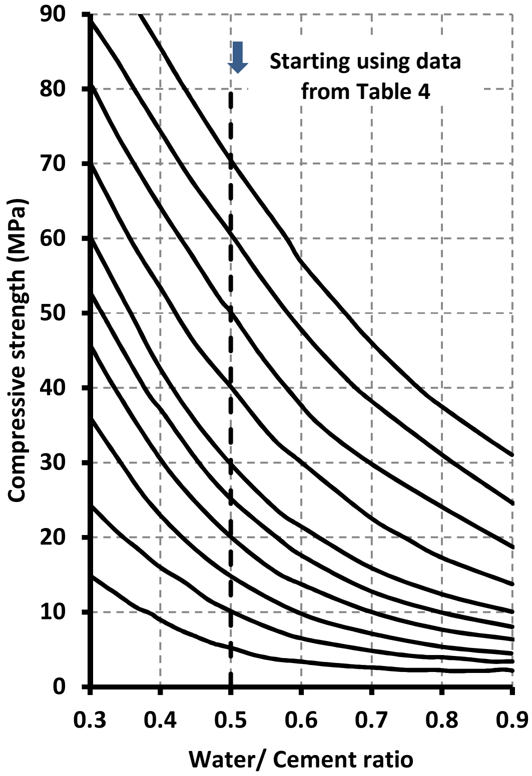

Figure 1: Relationship between compressive strength and free-water/cement ratio [10].

Table 5: Approximate free-water concrete (kg/m^3) required to give various levels of workability [10].

Slump (mm)		0-10	10-30	30-60	60-180
Vebe time (s)		>12	6-12	3-6	0-3
Maximum size of 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

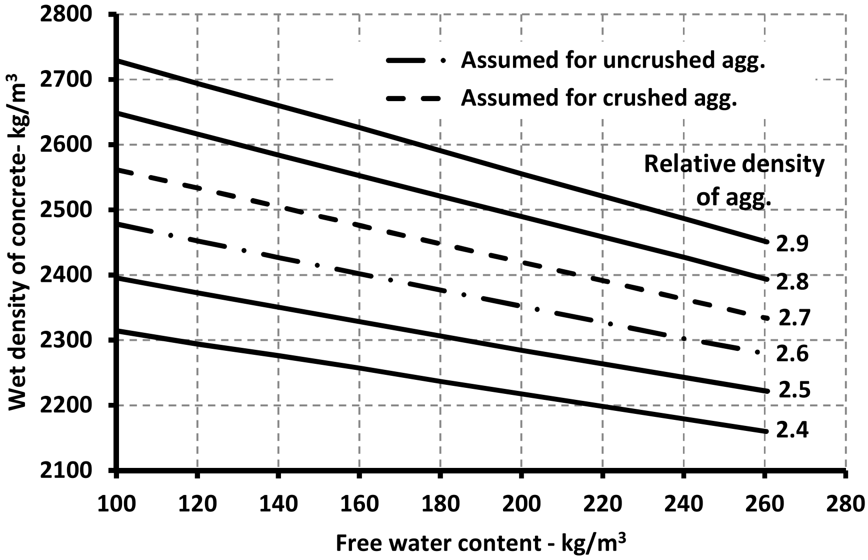

Figure 2: Estimated wet density of fully compacted concrete [10].

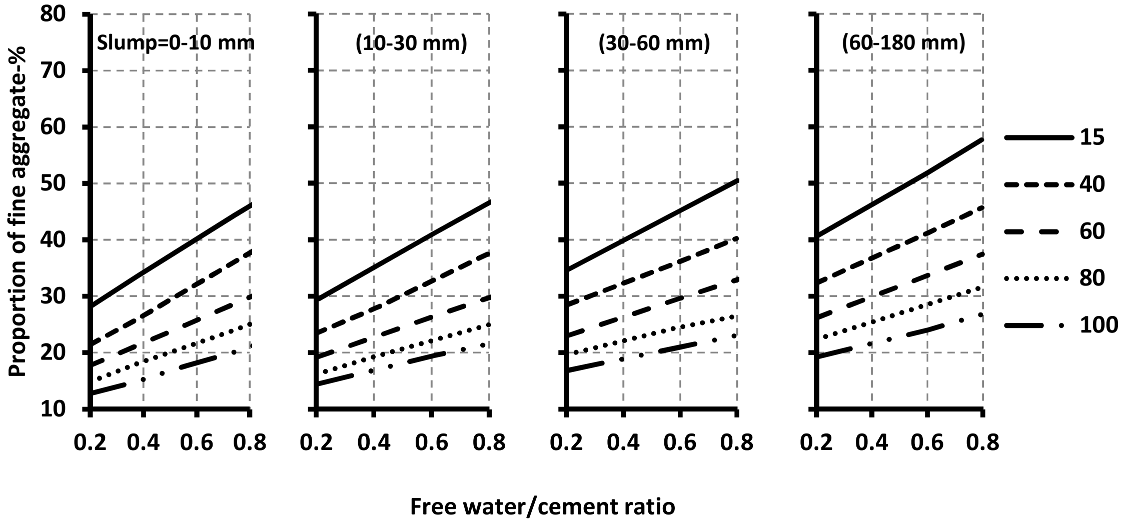

Figure 3: Recommended proportions of fine aggregate according to percentage passing a 600 μm sieve [10].

2.2 Results of mix design

Appling the procedures mentioned in Section 2.1, the results obtained for six concrete mixes using crushed and uncrushed coarse aggregate based on both American and British methods are shown in Figures 4 to 9.

It was noted from previous procedures that the American method specifies a constant value for the amount of gravel for each strength level, while the amount of sand will vary based on the

total volume of concrete mix. The same cannot be said for the British method, where both of gravel and sand have variable values depending on the density of fresh concrete and properties of the sand used. On this basis, American method ignored the type and nature of the aggregate used, while British method dealt with this criterion in detail. Subsequently, there were two options to design the concrete mix in British method, namely with crushed and with uncrushed aggregates.
It can be seen from Figures 4 and 5 that the calculated W/C ratios equivalent to various levels of compressive strength have clear differences between American and British methods especially at the lower strength values, then tend to be decreased at higher values. The percentage differences in W/C ratios were 21.5% and 24.5% for compressive strength values of 15 MPa and 25 MPa respectively using crushed aggregate. The corresponding percentages for uncrushed aggregate were 31.5% and 35.5% respectively.

If the values of compressive strength in the American method presented in Table 2 represent the strength of cylinder (A. M cylinder st.) rather than cubic specimens (A. M cube st.) and the 42.5 strength class of cement (B.M 42.5 st.) in the British method presented in Table 4 replaced by class of 52.5 (B.M 52.5 st.), the percentage differences in the calculated W/C ratios will be minimal, as shown in Figures 4 and 5.

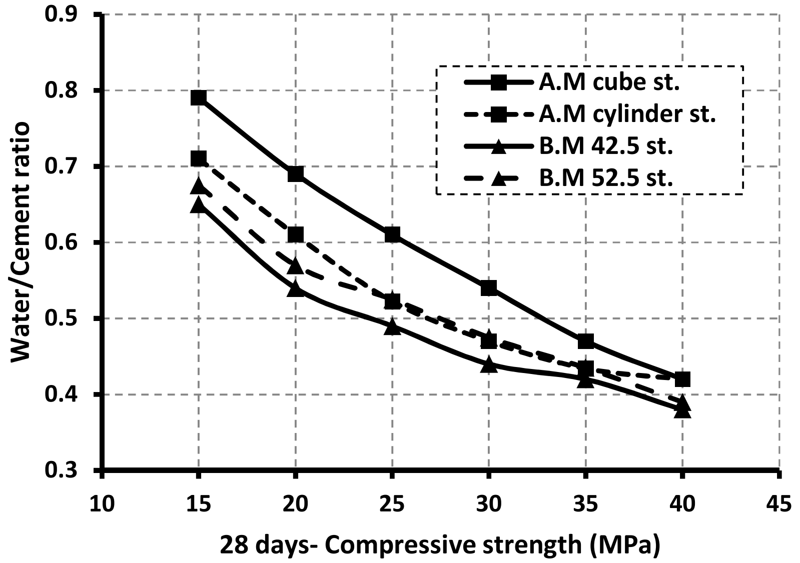

Figure 4: Compressive strength-W/C ratio relationship for concrete mixes using crushed aggregate.

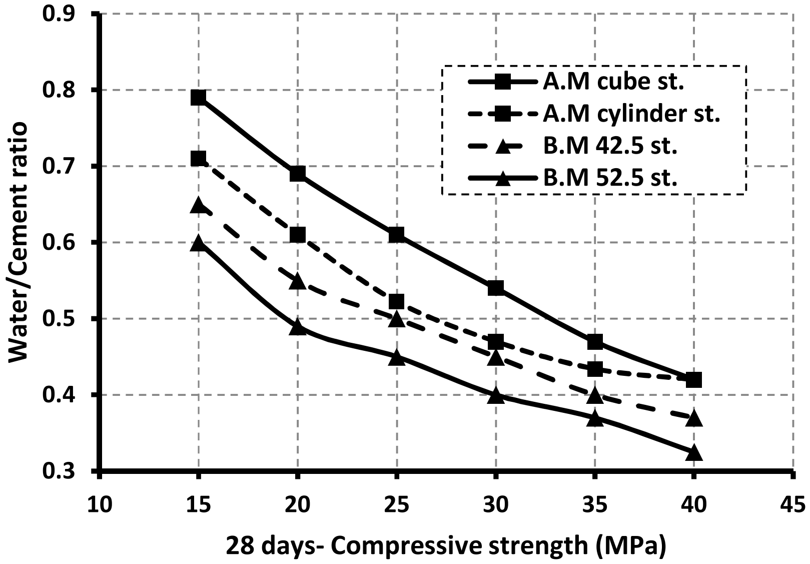

Figure 5: Compressive strength-W/C ratio relationship for concrete mixes using uncrushed aggregate.

The sand/cement ratio corresponding to the required strength level of concrete exhibited similar behaviour to that of strength-W/C ratio relationship and ranging from 1.14 to 3.25, as shown in Figures 6 and 7. It was clearly shown that the sand/cement ratio decreases with an increase of the concrete strength. This means increase the cement content required to obtain the specified strength level.

The percentage differences in the sand/cement ratio calculated based on the American method with those obtained from the British method for concrete mixes of 15 MPa and 25 Mpa 28-days compressive strengths with crushed aggregate were 21.7% and 30% respectively. The corresponding percentages for concrete mixes containing uncrushed aggregate were 9.5% and 24.5% respectively.

Applying the assumptions of cylinder strength for the American method and cement strength class of 52.5 for the British method, the aforementioned percentages will be highly decreased for the concrete mixes of crushed aggregate, as shown in Figure 6. However, the variation between the two methods still apparent for the concrete mixes containing uncrushed aggregate, as shown in Figure 7.

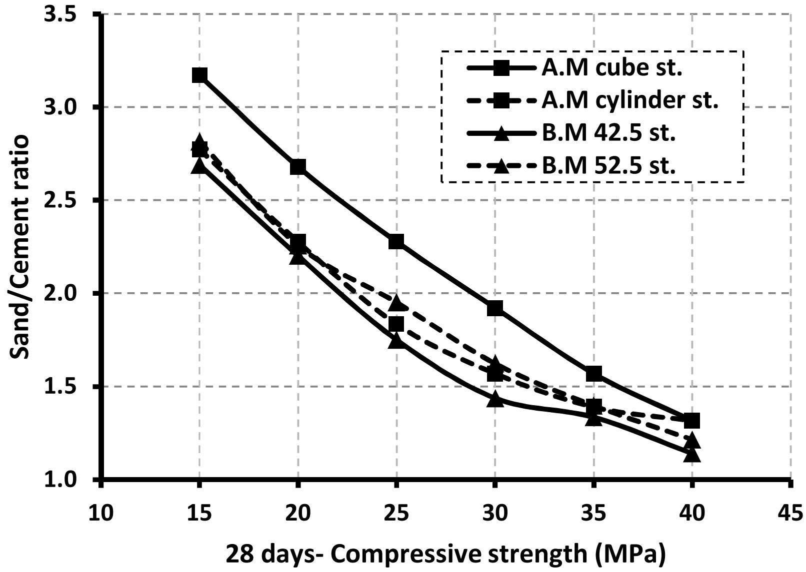

Figure 6: Compressive strength-Sand/Cement ratio relationship for concrete mixes using crushed aggregate.

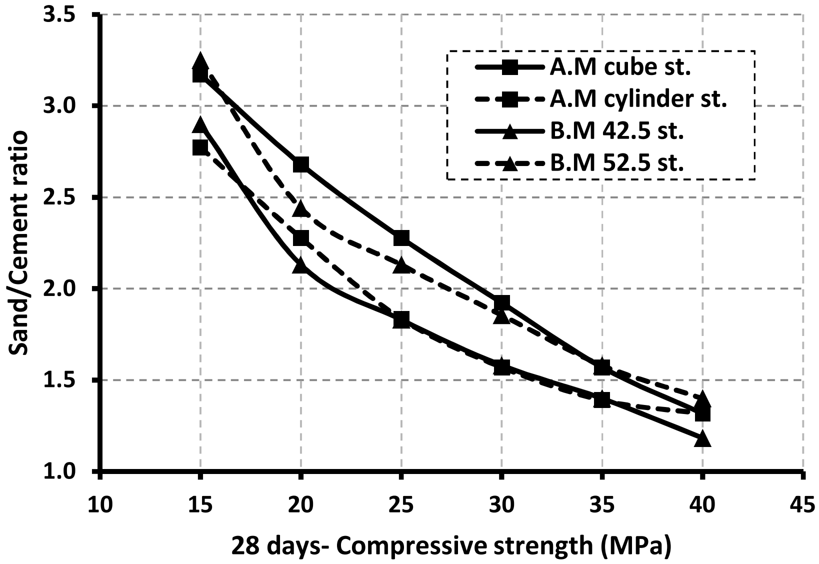

Figure 7: Compressive strength-Sand/Cement ratio relationship for concrete mixes using uncrushed aggregate.

The highest variation between the American and British design methods was noted in calculation the gravel/ cement ratio for the concrete mixes with various level of compressive strength, as shown in Figure 8. This attitude was lower for the mixes of uncrushed aggregate, as shown in Figure 9. The ratio of gravel/cement was ranging from 1.93 to 3.25.

In general, the value of compressive strength has inverse linear relationship to the gravel/cement ratio. This is due to the higher cement content required to provide cohesion and adhesion properties for the aggregate particles [8].

Significant converge in the ratio of gravel/ cement for both mix design methods was obtained when the hypothesis of cylinder strength and 52.5 strength class of cement are applied to American and British mix design methods respectively, as shown in Figures 8 and 9. This is indicative for reliable approach to design the concrete mix.

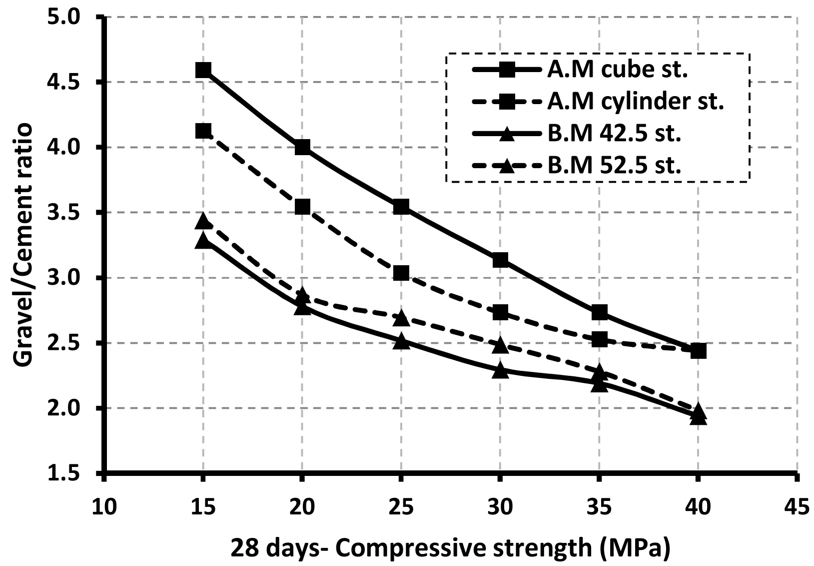

Figure 8: Compressive strength-Gravel/Cement ratio relationship for concrete mixes using crushed aggregate.

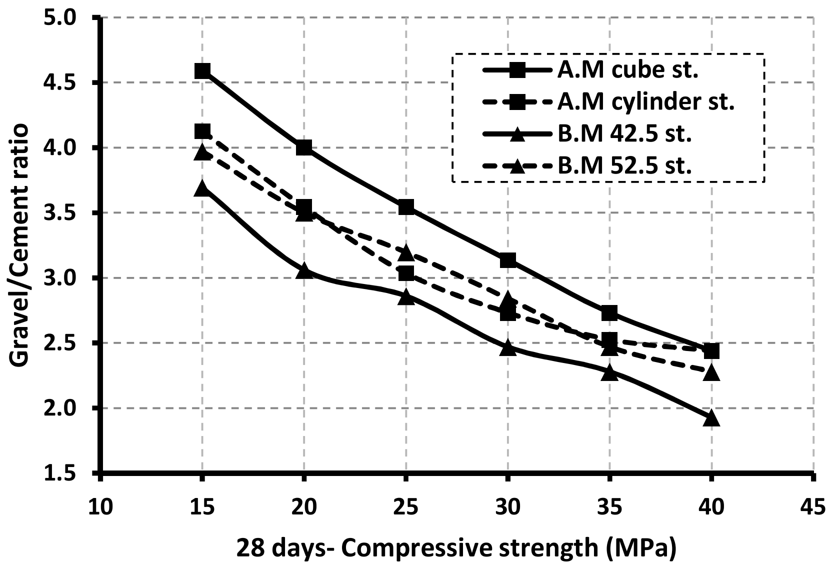

Figure 9: Compressive strength-Gravel/Cement ratio relationship for concrete mixes using uncrushed aggregate.

3. Experimental programme

In order to validate the calculated mix proportions, an experimental investigation has been carried out to measure the compressive strength of twelve concrete mixes; six of them were designed according to the American method and the other according to the British method. For each design method, three levels of 28 days compressive strength were adopted (15 MPa, 21 MPa and 30 MPa). The latter were formulated using crushed and uncrushed coarse aggregate. It is necessary to design the mix to have a mean strength greater than the specified characteristic strength by an amount termed the margin [10]. Thus:

$$f_m = f_c + ks$$

Eq.1

where f_m = the target mean strength;

f_c = the specified characteristic strength;

ks = the margin, which is the product of:

k = a constant equivalent to the degree of confidence and normally taken as 1.64;

s = the standard deviation, for 20 or more results s = 4 or can be calculated as follows:

$$s = \sqrt{\frac{\sum(x-m)^2}{n-1}}$$

Eq.2

where x = an individual result;

n = the number of results;

m = the mean of the n results.

Applying Eq.1, the target mean strength of the investigated concrete mixes will be 21.5 MPa, 27.5 MPa and 36.5 MPa respectively. For each mix, the fluidity aspect was checked in terms of the consistency to satisfy the requirements of workability. This was done by measure the concrete slump according to BS 1986 [11]. The moisture conditions of the aggregate is the major parameter affected the workability, so the W/C ratio has been adjusted each time to get the accepted range of slump (75-100) mm. The ratio of water absorbed by aggregate particles was found to be 1.95% .

3.1 Materials used

Ordinary Portland cement type (Crista) consistent with the requirements of Iraqi Standards (I.S.S) No.4 – 1984 [12] was used in this study. Locally available sand provided from quarry at the city of Najaf-Iraq was used as a fine aggregate. It was comply with the Iraqi Standards (I.S.S) No.45– 1984 [13]. Two types of coarse aggregate were used: crushed and uncrushed. They were locally available and supplied from Badra quarry. Both of the former coarse aggregates satisfy the requirements of the Iraqi Standards (I.S.S) No.45– 1984 [13]. Table 6 presents the properties of cement, fine and coarse aggregates used in this study. On the other hand, Figure 10 shows the nature of the coarse aggregate particles.

The preparation of specimen moulds, casting of the concrete samples and compaction operations were performed according to BS EN12390-1, 2 [14, 15]. After 24 hours the samples were taken out of their moulds (demoulded), marked and immersed in a basin of water at a temperature of 20 ± 2 ˚C until the date of the test.

3.1 Compressive strength test

The compressive strength of 150 mm cube specimens was measured in correspondence with BS EN 12390-3 [16] using a digital controlled compression machine with a maximum load capacity of 2000kN, as shown in Figure 11. A constant loading rate of 0.3 MPa/s was adopted throughout the test. Load was monitored until specimen failure and the maximum load in kN was recorded. This test was carried out at curing ages of 3, 7, 28 and 45 days and the average value of three samples was taken.

Table 6: Properties of cement, fine and coarse aggregates used in this study

Ordinary Portland cement			Fine aggregate			Coarse aggregate (Crushed and Uncrushed)		
Property	**Test Result**	**I.S.S No.45-1984**	**Sieve (mm)**	**% Passing**	**I.S.S No.45-1984**	**Sieve (mm)**	**% Passing**	**I.S.S No.45-1984 (5-40)**
3 d-st.	16.67	> 15 MPa	10	100	100	37.5	100	100
7 d-st.	23.00	> 23 MPa	4.75	100	90-100	19	54	30-70
C2S	25.0%	-----	2.36	86	60-95	13	23	-----
C3S	52.0%	-----	1.18	69	30-70	9.5	10	10-30
C3A	11.8%	-----	0.60	37	15-34	4.75	0	0-10
C4AF	8.20%	-----	0.30	8	5-20	2.36	0	0-5
-----	-----	-----	0.15	2	0-10	-----	-----	-----
Salts in terms of SO_3			0.33		0.5%	0.08		0.1%

(a) (b)

Figure 10: Nature of the coarse aggregate particles used: (a) crushed gravel, (b) uncrushed gravel

Figure 11. Digital controlled compression machine used in compressive strength test

4. Results and discussions

The results obtained of the experimental programme are shown in Figures 12 to 15.
It can be seen that the W/C ratio decreases with an increase of compressive strength for both designed and measured results. On the other hand, the amount of mixing water required to obtain the specified slump level (75-100) mm in the experimental approach was higher than that calculated in the design approach and increases with an increase in the value of the compressive strength, as shown in Figure 12. This was expected due to the water required to overcome the interior fraction between the aggregate particles as well as the absorption aspect which depends on the moisture condition of aggregate. Such behaviour was taken in consideration in both American and British methods. The quantity of water presented in Tables 1 and 5 refers to the free water which only contribute in the hydration process of cement and no allowance has been made for the water absorbed by aggregate particles.
The percentages increase in the measured W/C ratios compared with those calculated based on the British method for concrete mixes with compressive strength of 21.5 MPa and 36.5 MPa were 18.2% and 36.8% and based on the American method were 2.2% and 14.5% respectively. If the ratio of water absorbed by the total weight of aggregate particles (1.95%) is excluded, the aforementioned ratios for the British method will be 10.3% and 21.7% respectively. The corresponding ratios according to the American method are (-16.5%) and (-3.8%) respectively. These results are consistent with the conclusion referred to in Section 2.2 and presented in Figure 4. Lower tendency for water demand was noted for concrete mixes containing uncrushed aggregate at lower compressive strength. On the other hand, concrete mixes with higher values of compressive strength exhibited different behaviour, as shown in Figure 13.

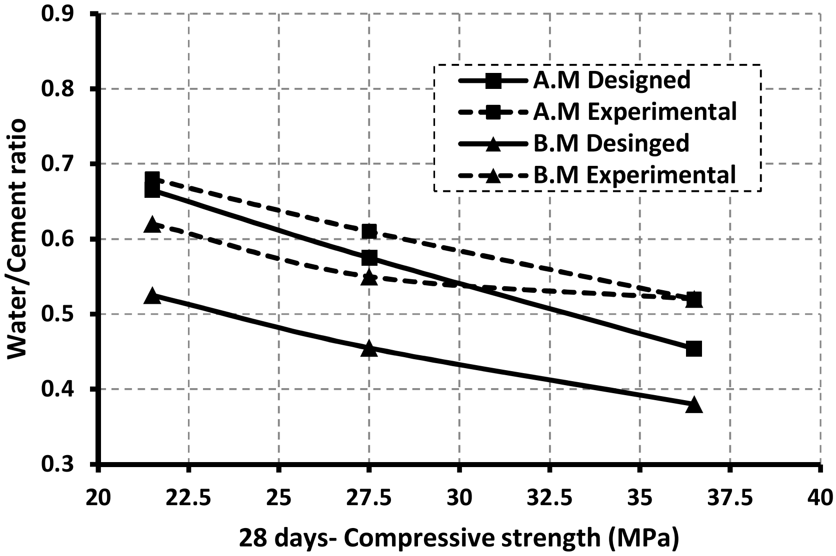

Figure 12. Water/ Cement ratio for various concrete mixes containing uncrushed aggregate

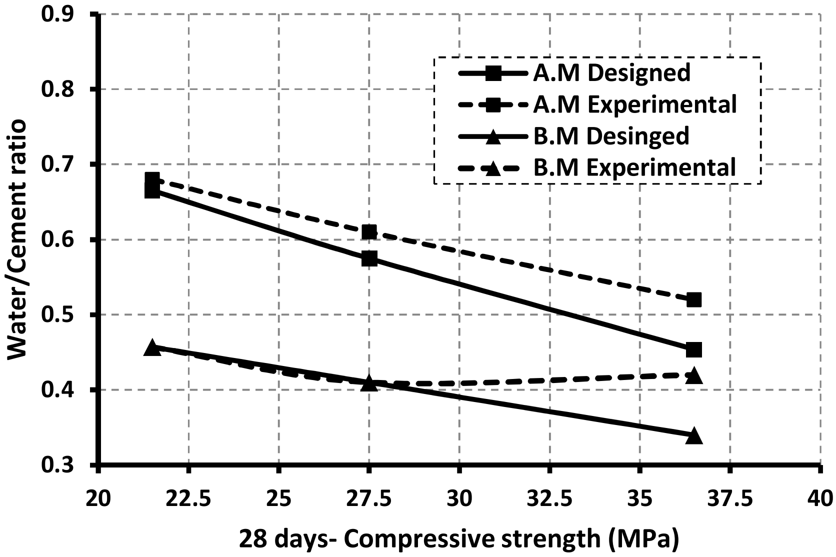

Figure 13. Water/ Cement ratio for various concrete mixes containing uncrushed aggregate

Figures 14 and 15 show the results obtained of the compressive strength at different sample age for various concrete mixes containing both crushed and uncrushed aggregates.

It can be seen that the concrete mixes designed based on both American and British methods for crushed aggregate satisfied the required strength level at 28 days. A close agreement between the measured results was observed, as shown in Figure 14. This behaviour confirms the above explanation for the results obtained of W/C ratio and suggestions for calculation mix proportions using both American and British methods as presented in Sections 2.2.

All of the concrete mixes containing uncrushed aggregate exhibited lower compressive strength than those designed at 28 days and considered being defective in this criterion, as shown in Figure 15. The progress of compressive strength was unnoticeable. This behaviour was unclear and may be due to the bad storage of cement used in these mixes which lead to pre-hydration of cement particles.

In general, the values of compressive strength for the concrete mixes containing both crushed and uncrushed aggregate and designed according to the British method were higher than those for American method at early ages (3 and 7days) and at later ages (45 days). This is related to the design concept adopted by the British method which emphasis on the requirements of durability [10]. This in turn means increase the value of compressive strength.

The expression suggested by BS EN 1992-1-1 [17] for estimating the compressive strength at time (*t*) for concrete of a normal weight from the strength at 28 days age has been evaluated to investigate its consistency with the obtained compressive strength results of this study. The expression is as below:

$$f_{cm}(t) = \beta_{cc}(t) f_{cm}$$
Eq.3

$$\beta_{cc}(t) = exp\left\{s\left[1 - \left(\frac{28}{t}\right)^{1/2}\right]\right\}$$
Eq.4

where f_{cm} is the mean compressive strength (MPa) at 28 days; t is the age of the concrete sample in days and s is a coefficient whose value depends on the type of cement and is typically in the range of 0.2-0.38.

Using the results obtained in this study, the calculated results showed that Eq.3 can only be applied to predict the values of compressive strength for concrete mixes having target mean strength of 21.5 MPa and 27.5 MPa using with s value of 0.29. The concrete mix with mean strength of 36.5 MPa may be classified as high strength concrete, so the aforementioned expression needs to be amended to suit such strength level.

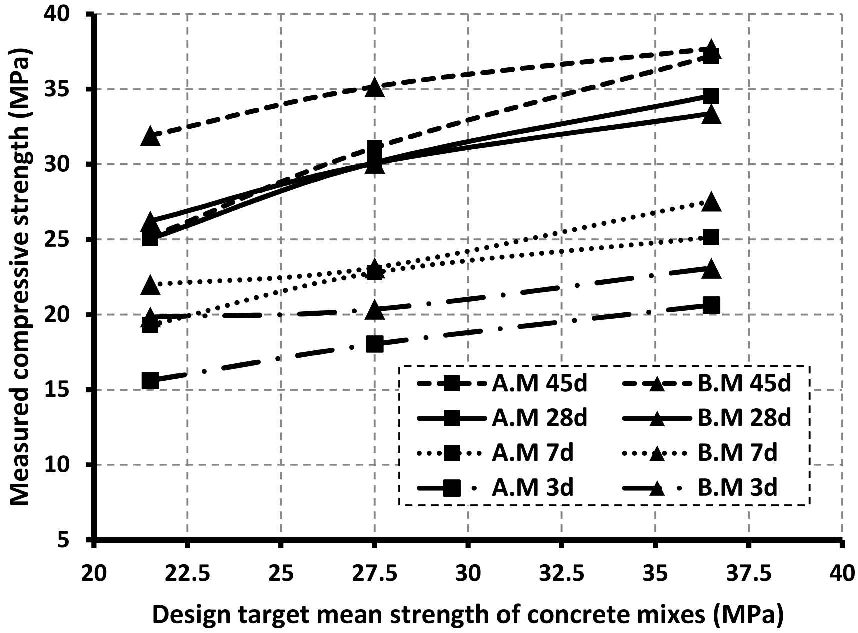

Figure 14. Values of compressive strength for various concrete mixes containing crushed aggregate

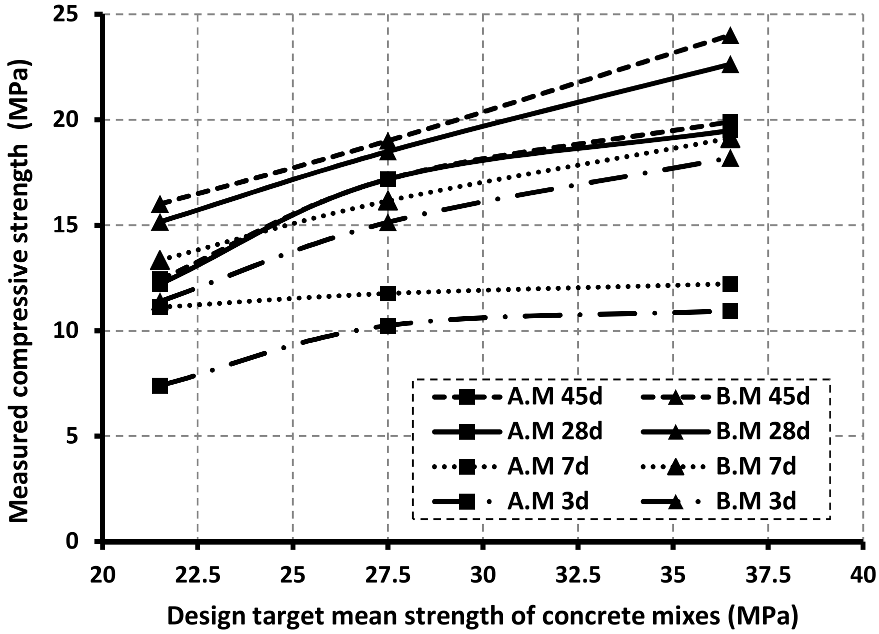

Figure 15. Values of compressive strength for various concrete mixes containing uncrushed aggregate

Taken in consideration the measured results of W/C ratio and compressive strength, a more precise estimate can be obtained for the of gravel/sand ratio from the following equation [8]:

$\rho = 10_{\gamma a}\,(100 - A) + C\left(1 - \frac{\gamma_a}{\gamma}\right) - W(\gamma_a - 1)$
Eq.5

where
ρ is the density (unit weight) of fresh concrete, kg/m^3;
γa is the weighted average bulk specific gravity (SSD) of combined fine and coarse aggregate; this needs to be determined from tests;
A is the air content, %;
C is the cement content, kg/m^3;
γ is the specific gravity of cement (generally 3.15 for Portland cement);
W is the mixing water requirement, kg/m^3;
The volume method is an exact procedure for calculating the required amount of fine aggregate. Here, the mass of fine aggregate, Af, is given by

$A_f = \gamma_f\left[1000 - \left(W + \frac{C}{\lambda} + \frac{A_c}{\gamma_c} + 10A\right)\right]$
Eq.6

where
A_c is the coarse aggregate content, kg/m^3;
γ_f is the bulk specific gravity (SSD) of fine aggregate;
γ_c is the bulk specific gravity (SSD) of coarse aggregate.

Applying Eqs. 5 and 6, the gravel/sand ratio for both American and British methods need to be amended. This implying increases the gravel/sand ratio for the American method and decreases it in the British method. Such tend is similar to that suggested in Sections 2.2 If compared with the equivalent sand/cement and gravel/cement ratios , as shown in Figures 16 and 17.

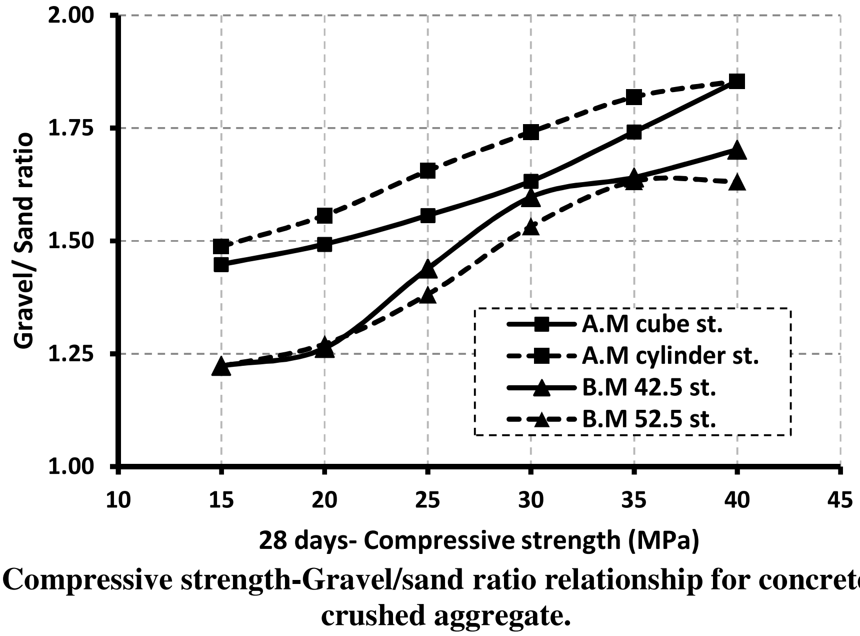

Figure 16. Compressive strength-Gravel/sand ratio relationship for concrete mixes using crushed aggregate.

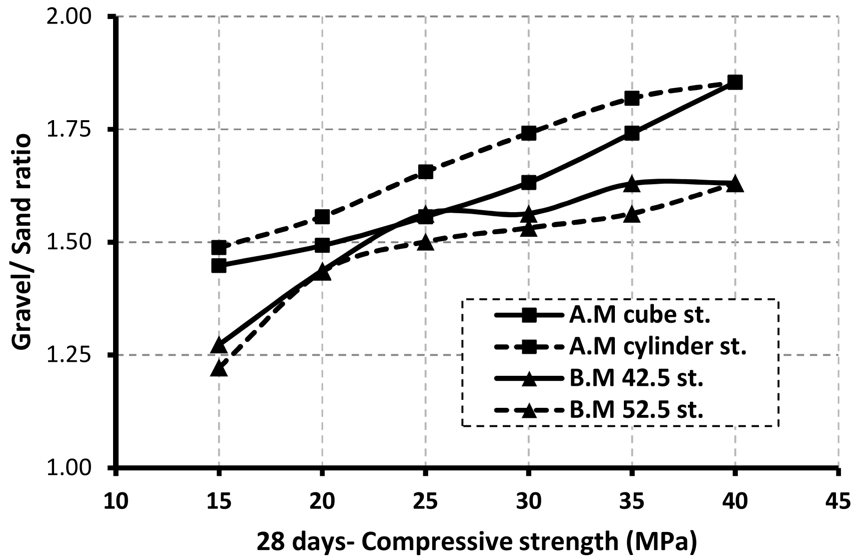

Figure 17. Compressive strength-Gravel/sand ratio relationship for concrete mixes using uncrushed aggregate.

5. Conclusions

This study was undertaken to evaluate the American and British methods for mix design using both analytical and experimental approaches. The main findings are listed below.

1. The American method disregarded the type of coarse aggregate used in concrete mix, whilst the British method emphasized on this feature.
2. The British method usually produces a concrete with more strength than that designed by American method. Such technique has inverse effect on the workability of the fresh concrete.
3. If the strength of cylinder specimens is adopted in the tabulated values of American method and the lower value of the cement strength class is used in the British method, the differences in calculation of mix proportions will be minimized.
4. The experimental results of compressive strength and workability showed close agreement with the suggested approach for calculation the mix proportions.
5. The concrete mixes containing uncrushed aggregate exhibited unclear behaviour in terms of the compressive strength and need for further attention to explore the correct tendency.
6. The formula suggested by BS EN 1992-1-1 [17] was reliable to estimate the value of compressive strength at time (*t*) for the range of normal strength concrete.

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