An Approach for Designing Different Sustainable and Economical Concrete Mixes

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Abstract. The design of sustainable and economic concrete mixes can be considered as a potential challenge for building's engineers and experts. Thus, this paper presents the possibility of designing such concrete mixes using low to moderate amounts of cement and using waste glass and steel slag powders. The use of three groups from concrete mixes have been prepared by control mix, 20% cement replacement, 25% cement replacement and 30% cement replacement by such powders. The compressive strength, flexural strength, splitting tensile strength and the dry density of concrete have been studied. Besides, the economic efficiency for the different concrete mixes has also been studied. The results show that the use of combination of glass and steel slag powders of 20% replacement of cement (10% each) exhibited a significant balance between strengths values and economical consideration.

Keywords: Economical efficiency, Steel slag powder, Glass powder, Sustainable Concrete.

1. Introduction
The primary concern of the modern world is sustainable development. When applied to building construction, the ideals of sustainable development can improve a community's economic well-being as well as its environmental health [1]. As a result, it appears that greening the masonry materials business is more beneficial for improving existing processes rather than developing new goods or processes [2, 3]. Due to the unique characteristics of concrete, it is considered durable and sustainable building material, widespread availability of its constituents, as well as has an extremely long service life [4, 5]. But the main binder of concrete is Portland cement. The demand for cement in 2015 was at the range of about 4.2 billion metric tons. The existing technology for the cement clinkers production is environmentally stressful due to much energy consumption and natural resources as well as the emission of pollutants.
Cement production actually accounts for about 5 percent of the total CO2 released and correlated to global warming. One ton from Portland cement clinker emits CO2 between 0.8 to 1 tons into the atmosphere [4, 6-7].

Consequently, reducing the cement amount by using the supplementary cementitious materials necessarily decreases the needed energy for the production of cement and CO2 liberation. This choice also permits a cost reduction for the manufacturing of cement due to several items. Such items include; saving the burning costs, decrease of released pollutants at the production stage of clinker, and a reduction of landfill areas occupied by such industrial by-products will provide significant ecological advantages for this type of cement. Furthermore, the use of mineral additives in the order of higher volumes for such industrial by-products gives important economic and ecological impacts [6].

2. Objectives of the Study
The objectives of this study are to present an approach for designing the concrete mix by the consideration of the cost and strength requirements. Thus, the low to moderate cement content with different percentages of glass and steel slag powders as partial replacement of cement have been used for such aim.

3. Materials, experimental program and testing
3.1. Material properties
Ordinary Portland Cement Type I which has been supplied by Badoush expansion cement factory were used in this study. This type of cement conforms to ASTM C150 [8] and its chemical properties are presented in Table 1. This study used glass powder and steel slag powder with particle sizes smaller than 63m and specific gravity values of (2.62) and (3.47). Table 2 and Table 3 detail the chemical analyses of glass powder and steel slag powder, respectively. They are in agreement with ASTM C618 [9] and ASTM C989 [10]. Superplasticizer has been provided by Sika ViscoCrete hi-tech 1316. This superplasticizer has satisfied the ASTM C 494, Type F [11]. The natural river sand used as a fine aggregate was supplied from Kanhash region in Mosul. Its specific gravity, fineness modulus and absorption of sand are (2.66), (3) and (1%), respectively. Potable water was used for mixing and curing processes. A rounded aggregate with a nominal maximum size of 10 mm was employed from the Khazer region of Mosul, Iraq, with specific gravity and water absorption of (2.68) and (0.4%), respectively.

Table 1. Ordinary Portland Cement (Chemical Composition)

| Constituent | Percent (%) | ASTM C150[8] (%) |
|-------------|-------------|------------------|
| SiO₂        | 20.893      | ----             |
| Al₂O₃       | 5.958       | ----             |
| CaO         | 62.476      | ----             |
| MgO         | 3.792       | max, 5.0         |
| SO₃         | 2.316       | max, 2.8         |
| Fe₂O₃       | 2.525       | ----             |
| L.O.I       | 1.449       | max, 4.0         |
| C₃S         | 39.485      | ----             |
| C₂S         | 30.157      | ----             |
| C₃A         | 11.61       | ----             |
| C₄AF        | 7.681       | ----             |
Table 2. Glass Powder (Chemical Composition)

| Constituent | Percent (%) | Pozzolan class N ASTM C618[9] (%) |
|-------------|-------------|-----------------------------------|
| SiO₂        | 73.698      | ----                              |
| Al₂O₃       | 0.717       | ----                              |
| CaO         | 10.433      | ----                              |
| MgO         | 1.273       | ----                              |
| SO₃         | ------      | max, 4                            |
| Fe₂O₃       | 0.371       | ----                              |
| Na₂O        | 12.706      | ----                              |
| TiO₂        | 0.085       | ----                              |
| K₂O         | 0.702       | ----                              |
| L.O.I       | ------      | max, 10                           |
| SiO₂ + Al₂O₃ + Fe₂O₃, min. percent | 74.8 | min, 70 |

Table 3. Steel Slag Powder (Chemical Composition)

| Constituent | Percent (%) | ASTM C989[10] (%) |
|-------------|-------------|-------------------|
| SiO₂        | 18.729      | ----              |
| Al₂O₃       | 2.181       | ----              |
| CaO         | 44.268      | ----              |
| MgO         | 5.537       | ----              |
| SO₃         | 0.457       | Max, 2.5          |
| Fe₂O₃       | 22.692      | ----              |
| Na₂O        | ------      | ----              |
| K₂O         | 0.011       | ----              |
| L.O.I       | 6.115       | 10                |
| Total Alkalis | 0.006579 | Min, 0.6          |
| (Na₂O + 0.658 K₂O) | Max, 0.9 |

3.2 Mix Proportions

To cover this observation, three group mixes were created, all of which were based on the same control mixes. The concrete C30, C25 and C20 were designed using the British approach of the Building Research Establishment (1988). The amount of cement content was 350 kg per cubic meter for the first group of the concrete mixes. The amount of cement for the second group concrete mix is 315.8 kg per cubic meter. And, the amount of cement content is 279.1 kg per cubic meter. Each group consists of control mix and mix with 20% replacement of cement by steel slag powder and glass powder by the order of 10% for each. Also, the rest mixes for each group consists of 25% of cement replacement by 10% steel slag with 15% glass powder and also the mix with 30% of cement replacement by 15% steel slag powder with 15% glass powder concrete.

The water to binder ratios were 0.36, 0.38 and 0.43 for the mix group 1, group 2 and group 3, respectively.
The use of 0.8% of superplasticizer of cement weight has been used for all groups’ mixes to maintain the workability by the range of 100 ±20 mm. Table 4 shows the concrete group mixes for the produced concrete in this study.

Table 4. Mix Proportions of concrete mixes

| Mixes  | Cement (Kg/m³) | Steel slag (Kg/m³) | Glass powder (Kg/m³) | Sand (Kg/m³) | Gravel (Kg/m³) | Water/binder % | Superplasticizer % |
|--------|----------------|-------------------|----------------------|--------------|---------------|----------------|-------------------|
| M1     | 350            | -----             | 778.2                | 1243         | 0.36          | 0.8            |
| M1-20% | 280            | 35                | 778.2                | 1243         | 0.36          | 0.8            |
| M1-25% | 262.5          | 35                | 778.2                | 1243         | 0.36          | 0.8            |
| M1-30% | 245            | 52.5              | 778.2                | 1243         | 0.36          | 0.8            |
| M2     | 315.8          | -----             | 787.3                | 1284.5       | 0.38          | 0.8            |
| M2-20% | 252.6          | 31.6              | 787.3                | 1284.5       | 0.38          | 0.8            |
| M2-25% | 236.8          | 31.6              | 787.3                | 1284.5       | 0.38          | 0.8            |
| M2-30% | 221            | 47.4              | 787.3                | 1284.5       | 0.38          | 0.8            |
| M3     | 279.1          | -----             | 838.2                | 1270.5       | 0.43          | 0.8            |
| M3-20% | 223.3          | 27.9              | 838.2                | 1270.5       | 0.43          | 0.8            |
| M3-25% | 209.3          | 27.9              | 838.2                | 1270.5       | 0.43          | 0.8            |
| M3-30% | 195.3          | 41.9              | 838.2                | 1270.5       | 0.43          | 0.8            |

3.3 Test methods
All specimens for different ages have been cured in water tank until the time of testing.

Three cubes 100 mm ×100 mm × 100 mm specimens were used for each mix to test the compressive strength at various ages 7 and 28 days according to BS1881:1992[12]. Also, the average of three cubes from the same size used in compressive strength have been used for testing the density according to ASTM C642 [13].

The average of three cylinders with D=100 mm and H= 200 mm has been used to determine the splitting tensile strength according to ASTM C496 [14]. The flexural strength has been achieved according to ASTM C78 [15] using the average of three prism of 100 mm x 100 mm x 400 mm at 7 and 28 days.

4. Test results and discussions
4.1 Compressive Strength
From the results tabulated in Table 5, it can be observed that the replacement of cement by 20% of steel slag and glass powders gives acceptable ranges of compressive strength for all group mixes. The relative strengths are ranged from about 85 to 97% from the control mixes for all group mixes at 28 days. This is surely can be attributed to lessen amount of cement so the amount of calcium hydroxide produced from hydration is not sufficient to be reacted with silicate and aluminate that are existed in slag or glass powders [16-18]. However, this is still obviously encouraging results due to the reduction of cement obtained due to such replacements. The reduction of cement varied between 56 to 75 kg per cubic meter due to 20% of cement replacement for the three groups used in this study. Continuously, the results for the replacement of cement by 25% of steel slag and glass powders (10% steel slag + 15% glass powder) of all groups also indicate more interesting value. The reduction of cement varied by about 70 to 98 kg per cubic
meter due to 25% of cement replacement for the three groups used in this study with also acceptable ranges of strength. However, the other important results have been obtained by the use of 30% of steel slag powder and glass powder in the order of 15% from each. The reduction of cement varied by about 84 to 105 kg per cubic meter due to 30% of cement replacement for the three groups utilized in this study. Compressive strengths of group 1, group 2, and group 3 at 28 days were 30.799 MPa, 20.899 MPa, and 20.006 MPa, respectively. So, all these level of strengths are with acceptable ranges and can be used for structural application.

Table 5. Compressive Strength Results for concrete mixes

| Mixes     | Compressive strength (MPa) | Relative strength at 28 days compared to control mix for each group mix, % |
|-----------|---------------------------|--------------------------------------------------------------------------|
|           | 7 days | 28 days     |                                                                             |
| M1        | 33.593 | 43.636      | 100                                                                        |
| M1-20%    | 29.742 | 38.559      | 88.3                                                                       |
| M1-25%    | 27.123 | 31.714      | 72.7                                                                       |
| M1-30%    | 22.467 | 30.799      | 70.6                                                                       |
| M2        | 24.5   | 30.501      | 100                                                                        |
| M2-20%    | 20.482 | 29.545      | 97.2                                                                       |
| M2-25%    | 23.774 | 26.655      | 87.4                                                                       |
| M2-30%    | 17.881 | 20.899      | 68.5                                                                       |
| M3        | 25.609 | 33.484      | 100                                                                        |
| M3-20%    | 22.786 | 28.308      | 84.5                                                                       |
| M3-25%    | 17.023 | 22.545      | 67.3                                                                       |
| M3-30%    | 12.321 | 20.006      | 59.7                                                                       |

4.2 Flexural Strength

Table 6 gives the test results of flexural strength at 7 and 28 days. The flexural strengths have been increased with time for all group mixes used in this study. However, the flexural strengths have been slightly decreased with increased replacement ratio of glass and steel slag powder compared with control mix for all group mixes. However, such slight decreases in this property are in compatible with compressive strength and for the same cause listed in previous section. The regression analysis for all group mixes shows strong relationships between compressive strength and flexural strength as shown in Fig.1, Fig.2 and Fig.3 for group 1, group 2 and group 3, respectively.

Table 6. Flexural Strength Results for concrete mixes

| Mixes    | Flexural strength (MPa) |  |
|----------|-------------------------|-----|
|          | 7 days | 28 days |
| M1       | 5.69   | 6.967   |
| M1-20%   | 5.179  | 6.927   |
| M1-25%   | 5.570  | 6.164   |
| M1-30%   | 5.531  | 5.437   |
| M2       | 5.499  | 6.937   |
| M2-20%   | 5.484  | 6.749   |
| M2-25%   | 4.799  | 6.17    |
| Mix     | Compressive Strength | Flexural Strength |
|---------|----------------------|-------------------|
| M2-30%  | 4.429                | 5.906             |
| M3      | 4.499                | 5.833             |
| M3-20%  | 4.641                | 5.602             |
| M3-25%  | 4.594                | 5.344             |
| M3-30%  | 4.594                | 5.039             |

**Figure 1.** Relationship between Compressive Strength with Flexural Strength for group mixes "M1"

**Figure 2.** Relationship between Compressive Strength with Flexural Strength for group mixes "M2"
4.3 Splitting Tensile Strength

Table 7 shows the test results of splitting tensile strength at 28 days. The splitting tensile strength slightly decreased with increased replacement ratio of glass and steel slag powder compared with control mix for all group mixes. Also, such slight decreases in this property are in compatible with compressive strength. The regression analysis for all group mixes shows strong relationships between compressive strength and splitting tensile strength as shown in Fig.4, Fig.5 and Fig.6 for group 1, group 2 and group 3, respectively.

**Table 7.** Splitting tensile Strength Results for concrete mixes

| Mixes | Splitting tensile strength (MPa) 28days |
|-------|----------------------------------------|
| M1    | 2.849                                  |
| M1-20%| 2.76                                   |
| M1-25%| 2.121                                  |
| M1-30%| 2.055                                  |
| M2    | 2.255                                  |
| M2-20%| 2.209                                  |
| M2-25%| 2.018                                  |
| M2-30%| 1.801                                  |
| M3    | 2.466                                  |
| M3-20%| 1.933                                  |
| M3-25%| 1.685                                  |
| M3-30%| 1.532                                  |

**Figure 3.** Relationship between Compressive Strength with Flexural Strength for group mixes "M3"
Figure 4. Relationship between compressive strength with splitting tensile Strength for group mixes "M1"

![Graph 1](image1)

Figure 5. Relationship between compressive strength with splitting tensile strength for group mixes "M2"

![Graph 2](image2)
Figure 6. Relationship between compressive strength with splitting tensile Strength for group mixes "M3"

4.4 Saturated Surface Dry Density

The saturated surface dry density results of concrete for all mixes group either for control mixes or those containing glass powder and steel slag powder were determined according to ASTM C 642. The results of such concrete's densities at 28 days are tabulated in Table 8. The results showed that the mixes of group 1 exhibited a greater range of saturated surface dry densities than that for mixes group 2 or 3. However, this is obviously known related to the greater amount of cement ingredient in the concrete mixes for group 1 which possesses higher specific gravity than other ingredient [19]. On the other hand, the use of glass and steel slag powders decreases slightly the density due to the less amount of C-S-H formed due to the hydration of cement and also different weight of C-S-H produced from the pozzolanic reaction for the mixes containing glass and steel slag powders [20].

Table 8. Saturated Surface dry density Results for concrete mixes

| Mixes | Density (gm/cm³) |
|-------|-----------------|
| M1    | 2.490           |
| M1-20%| 2.480           |
| M1-25%| 2.430           |
| M1-30%| 2.415           |
| M2    | 2.425           |
| M2-20%| 2.415           |
| M2-25%| 2.405           |
| M2-30%| 2.395           |
| M3    | 2.40            |
| M3-20%| 2.380           |
| M3-25%| 2.370           |
| M3-30%| 2.360           |
5. Economic Efficiency criteria

Some logical steps were utilized to evaluate the sustainable concrete performance to study the economic efficiency of such mixes [21]. Thus, the cost for all mixes per cubic meter for concrete was calculated. These steps are mentioned here as follows:

Step 1: The maximum value in each column has been determined as shown in Table 9.

Step 2: Divide each value for the first three columns on the maximum value to determine the coefficient for each value. For the fourth column the coefficients have been determined using the result of dividing the value of cost for each mix to the maximum cost value then subtract it from 1.

Step 3: Find the total strength coefficient by assuming that the first three columns represent 50% as shown in Table 10.

Step 4: Find the total average coefficient for each mix, by adding the total strength coefficient with cost coefficient. The largest average coefficients present the best suitable mix.

| Mixes | Compressive strength (MPa) 28 days | Flexural strength (MPa) 28 days | Splitting tensile strength (MPa) 28 days | Cost (USD/m$^3$) |
|-------|-----------------------------------|---------------------------------|----------------------------------------|-----------------|
| M1    | 43.636                            | 6.967                           | 2.849                                  | 48.15           |
| M1-20%| 38.559                            | 6.927                           | 2.76                                   | 44.60           |
| M1-25%| 31.714                            | 6.164                           | 2.121                                  | 43.5            |
| M1-30%| 30.799                            | 5.437                           | 2.055                                  | 42.35           |
| M2    | 30.501                            | 6.937                           | 2.255                                  | 45.65           |
| M2-20%| 29.545                            | 6.749                           | 2.209                                  | 42.45           |
| M2-25%| 26.655                            | 6.17                            | 2.018                                  | 41.45           |
| M2-30%| 20.899                            | 5.906                           | 1.801                                  | 40.85           |
| M3    | 33.484                            | 5.833                           | 2.466                                  | 42.85           |
| M3-20%| 28.308                            | 5.602                           | 1.933                                  | 40.00           |
| M3-25%| 22.545                            | 5.344                           | 1.685                                  | 39.10           |
| M3-30%| 20.006                            | 5.039                           | 1.532                                  | 38.60           |
| Maximum Value | 43.636 | 6.967 | 2.849 | 48.15 |
Table 10. Coefficients Evaluation for Concrete Mixes

| Mixes | Coefficient of Compressive strength | Coefficient of Flexural strength | Coefficient of Splitting tensile strength | Total strength coefficient as equivalent to 50% from the total coefficient | Cost Coefficient 1-(value / max. value from table 9) | Total Average Coefficient |
|-------|-----------------------------------|---------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------------------|--------------------------|
| M1    | 1                                 | 1                               | 1                                        | 0.5                                              | 0                                           | 0.500                    |
| M1-20%| 0.884                             | 0.994                           | 0.968                                    | 0.474                                            | 0.0735                                      | 0.547                    |
| M1-25%| 0.726                             | 0.885                           | 0.744                                    | 0.392                                            | 0.0969                                      | 0.489                    |
| M1-30%| 0.706                             | 0.78                            | 0.721                                    | 0.368                                            | 0.120                                       | 0.487                    |
| M2    | 0.699                             | 0.995                           | 0.791                                    | 0.414                                            | 0.0519                                      | 0.466                    |
| M2-20%| 0.677                             | 0.968                           | 0.775                                    | 0.403                                            | 0.118                                       | 0.521                    |
| M2-25%| 0.61                              | 0.885                           | 0.708                                    | 0.367                                            | 0.1394                                      | 0.506                    |
| M2-30%| 0.479                             | 0.8477                          | 0.632                                    | 0.326                                            | 0.1515                                      | 0.478                    |
| M3    | 0.767                             | 0.837                           | 0.866                                    | 0.412                                            | 0.11                                        | 0.522                    |
| M3-20%| 0.649                             | 0.804                           | 0.678                                    | 0.355                                            | 0.169                                       | 0.524                    |
| M3-25%| 0.517                             | 0.767                           | 0.591                                    | 0.300                                            | 0.188                                       | 0.488                    |
| M3-30%| 0.458                             | 0.723                           | 0.53                                     | 0.285                                            | 0.198                                       | 0.483                    |

From the results obtained in Table 10, it can be seen that the use of 20% of glass and steel slag powders exhibited the highest coefficients compared with control mixes for all groups. However, it can be seen that the M1-20% gives the highest coefficient. Also the mixes M2-20% and M3-20% indicated higher coefficients than that of M1. This is also so interesting results and giving a new approach for sustainable concrete mix design to be assumed as the level of consuming cement in the concrete mixes are intended to be at least for environmental and economic purposes.

6. Conclusions
The following conclude it from the results of this study:

1. The replacement of 30% of cement by the combination of glass and slag powders gives suitable economic efficiency in different sustainable concrete mixes due to reduction of cement by about 84 to 105 kg per cubic meter.
2. The replacement of 20% to 25% of cement by the combination of glass and slag powders gives suitable structural strength for sustainable concrete mixes with reduction of cement by about 56 to 98 kg per cubic meter.
3. The use of 20% of cement replacement by combination of steel slag and glass powders can be considered as the best balance between strength and economic factor.
4. The flexural and splitting tensile strengths for sustainable concrete are in agreement with compressive strengths for such concrete. Thus, the 20% of cement replacement by steel slag and glass powders gives acceptable values with slight decrease compared with reference mixes.
5- The economic efficiency coefficient gives a good impression for selecting the best mixes depending on strength and cost criteria. Thus, the richest cement concrete which represents the moderate level of cement mix gives better performance regarding to these criteria compared with the lower or lowest cement concrete mixes.

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