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Dynamic mix design optimization of high-performance concrete

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Abstract. High performance concrete (HPC) depends on various parameters such as the type of cement, aggregate and water reducer amount. Generally, the ready concrete company in various regions according to the requirements and costs, mix design of concrete as well as type of cement, aggregates, and, amount of other components will vary as a result of moment decisions or dynamic optimization, though the ideal conditions will be more applicable for the design of mix proportion of concrete. This study aimed to apply dynamic optimization for mix design of HPC; consequently, the objective function, decision variables, input and output variables and constraints are defined and also the proposed dynamic optimization model is validated by experimental results. Results indicate that dynamic optimization objective function can be defined in such a way that the compressive strength or performance of all constraints is simultaneously examined, so changing any of the variables at each step of the process input and output data changes the dynamic of the process which makes concrete mix design formidable.

Keywords: high performance concrete; mix design; dynamic optimization

1. Introduction

High-performance concrete has the following characteristics simultaneously: easy placement, compaction without segregation, early age strength, long-term strength, mechanical properties, permeability, density, fracture energy, volume stability, and long life in severe environments; it should be noted that the above characteristics cannot be always achieved with regard to the constituent materials such as super plasticizer and the type of processing method of ordinary concretes (Goodspeedi *et al*. 1996, Mehta and Monteiro 2006, Shariati *et al*. 2011, 2012, 2014a, b, 2016, Bouteiller *et al*. 2012, Aghaee and Foroughi 2013, Konkov 2013, Mohammadhassani *et al*. 2014, Abedini *et al*. 2017, Khorami *et al*. 2017a, Nobakht *et al*. 2017, Bazzaz *et al*. 2018, Koloo *et al*. 2018, Toghroli *et al*. 2018, Paknahad *et al*. 2018).

The parameters influencing the strength and efficiency of high-performance concretes include the type of cement, the water-cement ratio, the type and amount of Pozzolanic materials, the type and amount of lubricants, and aggregates (Folliard and Berke 1997, Park *et al*. 2008).

Additives influence the concrete in different ways simultaneously; for instance, air entraining admixture decreases the permeability and compressive strength and increases the efficiency; use of fly ash results in reduction of the required water, temperature of the concrete, and costs; and silica fume increases the durability and strength of concrete and decreases lubricity and pumping. In addition, more expensive materials such as different coarse aggregates including concrete dust, super plasticizer, Nano additives and higher technologies are required to prepare ultra-performance concretes. (Eskandari-Naddaf *et al*. 2014, Institute 1998, Bassuoni and Nehdi 2005, Prasad *et al*. 2009, Aïtcin 2011, Grigonis *et al*. 2011, Nagrockienė *et al*. 2011, 2013, Lekūnaitė *et al*. 2012, Wang *et al*. 2012, Khorami *et al*. 201 b, Ziaei-Nia *et al*. 2018, Hosseinpour *et al*. 2018, Nasrollahi *et al*. 2018, Wei *et al*. 2018).

This type of concrete is used to construct long-span pre stressed concrete bridges, high-rise structures, concrete ships, highway industry, and severe environment in order to reach lower weight of structures, more cost-effective construction of structures, less repair and maintenance, and less time for construction (Zia 1993, Holm and Bremner 2000, Hájek and Fiala 2008, Shariati 2008, T. Parhizkar 2009, Khorramian *et al*. 2017, Akgul *et al*. 2017). Considering the fact that the mix design of this type of concrete depends on different parameters that play a very critical role in the performance level (Bonvin *et al*. 2001, Sherbaf and Eftekhar 2012, Eskandari-Naddaf and Kazemi 2017) and cost of concrete, the mix design methods for the high-performance concrete should be examined taking into consideration the parameter of costs in order to make this type of concrete more common. In this regard, dynamic optimization can be a suitable solution.

Optimization is the process of reaching the optimum result under existing conditions. Engineers have to make many managerial and technological decisions in several stages during construction and repair and maintenance of

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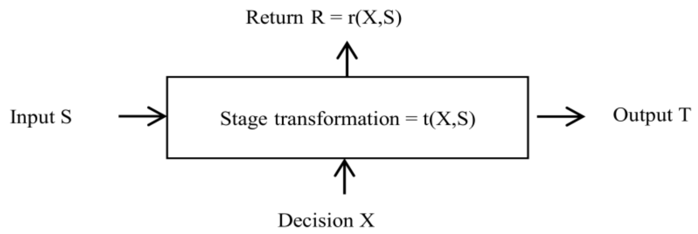

Fig. 1 Processing of dynamic optimization for one step

structures and engineering systems. The ultimate aim of these decisions is to minimize the required effort or to maximize the intended interest. Application of parametric methods in optimization in structural engineering designs have been used by many researchers (Mohammadhassani *et al*. 2013, 2014, Toghroli *et al*. 2014, 2016, Safa *et al*. 2016, Mansouri *et al*. 2017, Zandi *et al*. 2018). Generally, there is more than one acceptable solution or design, and optimization aims at comparing different designs and selecting one of them as the optimum design (Rao and Rao 2009, Fanaie and Dizaj 2014).

The dynamic optimization is an appropriate method for timely resolution of large scale practical problems (Ulanicki *et al*. 2007, Feng *et al*. 2010). It has been developed within the management of operational objectives so as to improve the performance of systems with regard to the quality in a specific managerial strategy in that more variables and more stages of decision making lead to more complicated and accurate problem-solving. (Sechi and Sulis 2009, Anghinolfi *et al*. 2013). One of the characteristics of this method is that the procedures and negative and positive items are mutually dependent (Lu *et al*. 2009). Furthermore, this method has been used in various cases, including optimization of energy consumption; optimal selection of routes and material transportation, products, and consumables in industries, and the like (Lambert and Harris 1990, Capón-García *et al*. 2013). Application of this method is also evident in cases where the linear and nonlinear optimization methods make the problem-solving very complicated (Hsiao and Chang 2002). The objective functions for optimization should be based on decision variables, limitations of decision, and resources (concrete constituent materials) (Brandt 1998, Hirschi *et al*. 2005). Most engineers believe that there is only one mix design for strength of concrete. However, there are actually numerous mix designs for mix design with certain strengths at any time considering the limitations of the time spent for preparation of the mix design. All these mix designs can supply the required compressive strength, but only one of them is the most cost-effective design.

In this research, 6 mix designs were designed for the high-performance concrete with different strengths shown in the following table, and the solution of one of the 6 designs was presented as an example of the dynamic method. The concretes produced through the mix designs relevant to the designed strengths were examined using the compressive strength test. The obtained strengths corresponded to the reality with a favorable approximate. The dynamic optimization method used in the concrete technology for the first time was applied for the high performance concrete.

2. Dynamic optimization theory

Dynamic programming is the mathematical method that was introduced for optimization of multistage decision making problems by Richard Bellman in early 1950, and the main characteristic of this method is its dependence on the time parameter. As the functional issues are performed using dynamic programming, a multistage decision process involves a set of interrelated single-stage processes in sucha way that the output (efficiency) of one stage is the input of the next stage. A decision process can be described with specific input parameters, S (or data), specific decision variables (X), and specific output parameters (T) showing the output obtained as a result of making a decision. The input parameters are called input state variables, and the output parameters are called output state variables. Then, a return function or an objective function R measures the effect of the made decisions and the output is the result of these decisions. Fig. 1 shows an example of a single-stage process.

The output (efficiency) is associated with the input through the single-stage conversion function shown in

$$T = t\,(X, S) \tag{1}$$

As the input state of the system affects the made decisions, the return function can be presented as follows

$$R = r\,(X, S) \tag{2}$$

A sequence of a multistage process can be presented briefly as shown in Fig. 2 (Rao and Rao 2009).

The model can be assumed as two-dimensional or three-dimensional. If the model is defined as three-dimensional, 3 outputs are examined in each stage, and these outputs include the changes in the effect on strength, the level of efficiency of concrete, and the amount of price. In this case, the effect of the 3 outputs is examined simultaneously and

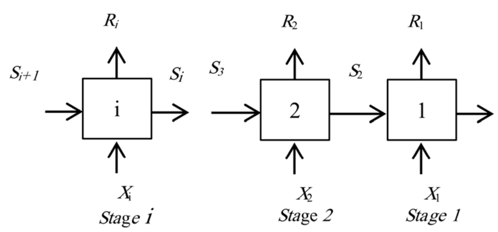

Fig. 2 Processing of dynamic optimization for multiple step

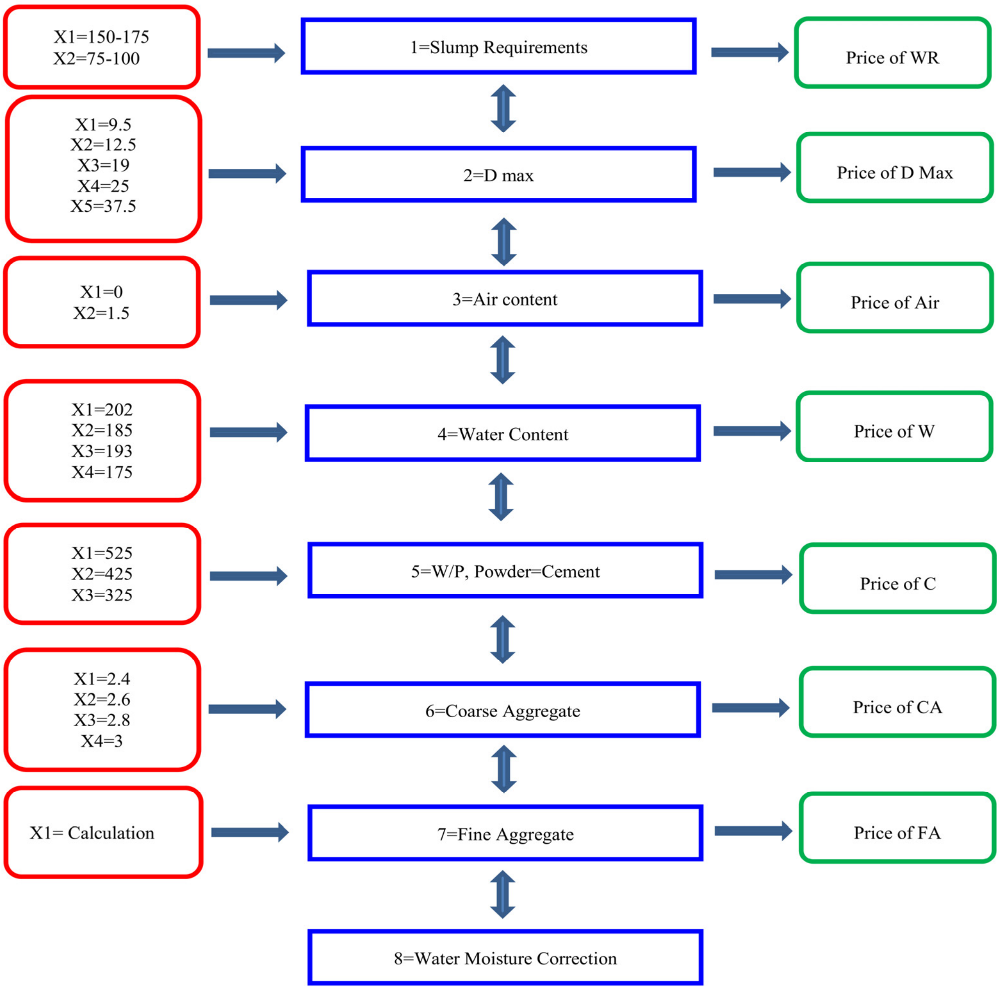

Fig. 3 Flow chart of dynamic mix design

concordantly in each stage. The limitations include the minimum and maximum allowable amount of the materials used in the relevant stage, that is, the decision variables (X). It should be noted that the volume and complexity of computations in this case will be very high because the parameters affect the strength, efficiency, and costs in each stage differently, and sometimes, the input parameters may not even affect the strength or efficiency in some stages. For example, the strength of the aggregates largely affects the hardened concrete although it does not have any effect on the concrete efficiency. Actually, the sensitivity analysis of each efficiency, strength, and cost parameters differs from one stage to another.

However, if the model is examined as two-dimensional, as in this case, one of the outputs is eliminated with regard to the priorities and their sensitivity analysis, or it may be assumed constant that is a subcategory of the first case. For example, considering the fact that the high performance is the matter of subject, in special large-scale projects where the financial limitation is of less importance, the output related to the cost can be discarded, and its changes that are less important can be ignored. In such a case, outputs related to each stage involve the strength and efficiency for which the minimum strength and maximum efficiency for the purpose of increasing the performance should be taken into consideration as the limitations relevant to the outputs (S & R) in each stage besides the limitations relevant to the inputs of that stage (X).

3. Proposed method

The design stages of the proposed mix design are presented below considering the fact that each stage is dependent on its previous stage: selection of slump, selection of the largest dimension of aggregates, estimation of the required amount of water and air (W & A), selection of water to cement ratio (W/C), calculation of the amount of cement (C), estimation of the amount of coarse aggregates (CA), and estimation of the amount of fine aggregates (gravel) (FA). The limitations of each stage should be taken into consideration. Fig. 3 shows the flowchart of this model.

In this problem, different values of decision variables, X1 to X7, include the parameters: 1. Slump; 2. Maximum dimension of the aggregate; 3. Amount of air; 4. Amount of water; 5. Water-cement ratio; 6. Amount of sand; 7. Amount of gravel; and 8, Humidity correction. Values of the variables S1 to S7 were the output of one stage and the input of its next stage. For example, S1 shows the amount of slump. It should be noted that these values are the output

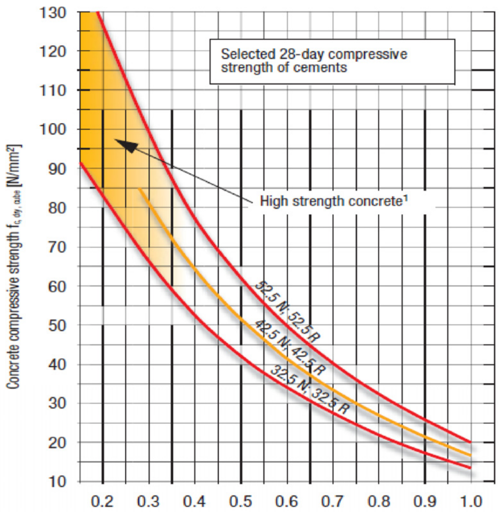

Fig. 4 Compressive strength vs W/C (Hirschi *et al*. 2005)

of stage 1 and input of stage 2. Moreover, regarding the cost of R parameters, the objective functions corresponding to the number of their stages are defined in the tables. For instance, R1 is the minimum cost of lubricant for achieving the desired efficiency corresponding to the initial efficiency of the concrete; and R2 is the minimum cost of aggregates per cubic meter of the concrete among different costs of aggregates. In this method, there were different routes for reaching the desired strength when supplying minimum level of efficiency and considering minimum cost for preparing the high-performance concrete. Depending on the selected materials, going through each of these routes in each stage would yield a cost that is different from that in other stages and should be minimized. In such conditions, each of the parameters, including subparameters of R, S, and even X, changes in each stage in terms of the effect of the materials used in the concrete on the efficiency or strength or both at any time. Other choices of different arameters in other states are influenced in order to optimize the mix design in terms of the mentioned dimensions. In this regard, other parameters would change in accordance to the changes in each variable at the time of choosing the mix design appropriate for the regional conditions, and this situation would result in optimization of the concrete mix design in this project. It should be noted that Fig. 4 was used to determine the amount of W/C because the Codes ACI-211 did not mention the effect of all varieties of cement on the amount of W/C.

Considering that this mix design did not contain only the cement, he water-cement ratio obtained from the figure was assumed to be equal to W/B to reach higher accuracy. As shown in Fig. 3, the mix design tries to adapt the design to the Codes ACI-211 in which the first stage was assumed to be the selection of slump, regardless of the modification of compressive strength. Based on the Codes ACI-211, the following values were specified: X1 = 150-175, X2 = 75-100, and X3 = 25-50. Given that the value of the slump X3 is very small, it was discarded as an input for making the problem easier and reducing the cost of HPC production. In addition, lubricants that increase the slump and facilitate the use of slump in HPC can be used to homogenize the materials in the first stage. The second stage of the design is the selection of the largest dimension of aggregates. This stage is very diverse and critical because the material, compressive strength, and cost of the aggregates largely affect the production. In the second part of the input parameters, the number of variables varies with the size of the aggregates. Aggregates comprise 5 sizes, and each size affects the cost, strength, and performance, as larger aggregates increase the strength. Furthermore, only the maximum size of the aggregates is used instead of the 5 input X parameters. It is worthy of note that the decrease in

Table 1 Sample dynamic mix design for 40 (MPa)

Slump (mm)	Air (%)	Water (Kg/m^3)	Kind of C	W/B	W/P	FM	CA/P	FA/P	WR (*Kg*)
150-175	0	202	52.5	0.68	0.43	2.40	1.8	1.9	0.0
	0	202	52.5	0.68	0.43	2.60	1.9	1.9	0.0
	0	202	52.5	0.68	0.43	2.80	2.0	1.9	0.0
	0	202	52.5	0.68	0.43	3.0	2.1	1.9	0.0
	1.5	185	52.5	0.68	0.40	2.40	1.7	1.9	0.0
	1.5	185	52.5	0.68	0.40	2.60	1.8	1.9	0.0
	1.5	185	52.5	0.68	0.40	2.80	1.9	1.9	0.0
	1.5	185	52.5	0.68	0.40	3.0	2.0	1.9	0.0
75-100	0	193	52.5	0.68	0.41	2.40	1.8	1.9	2.8
	0	193	52.5	0.68	0.41	2.60	1.9	1.9	2.8
	0	193	52.5	0.68	0.41	2.80	2.0	1.9	2.8
	0	193	52.5	0.68	0.41	3.0	2.1	1.9	2.8
	1.5	175	52.5	0.68	0.38	2.40	1.8	1.9	2.8
	1.5	175	52.5	0.68	0.38	2.60	1.9	1.9	2.8
	1.5	175	52.5	0.68	0.38	2.80	2.0	1.9	2.8
	1.5	175	52.5	0.68	0.38	3.0	2.1	1.9	2.8

Table 1 Continued

Slump (mm)	Air (%)	Water (Kg/m^3)	Kind of C	W/B	W/P	FM	CA/P	FA/P	WR (*Kg*)
150-175	0	202	42.5	0.63	0.43	2.4	1.8	1.9	0.0
	0	202	42.5	0.63	0.43	2.60	1.9	1.9	0.0
	0	202	42.5	0.63	0.43	2.80	2.0	1.9	0.0
	0	202	42.5	0.63	0.43	3.0	2.1	1.9	0.0
	1.5	185	42.5	0.63	0.40	2.40	1.8	1.9	0.0
	1.5	185	42.5	0.63	0.40	2.60	1.9	1.9	0.0
	1.5	185	42.5	0.63	0.40	2.80	2.0	1.9	0.0
	1.5	185	42.5	0.63	0.40	3.0	2.1	1.9	0.0
75-100	0	193	42.5	0.63	0.41	2.40	1.8	1.9	2.8
	0	193	42.5	0.63	0.41	2.60	1.9	1.9	2.8
	0	193	42.5	0.63	0.41	2.80	2.0	1.9	2.8
	0	193	42.5	0.63	0.41	3.0	2.1	1.9	2.8
	1.5	175	42.5	0.63	0.38	2.40	1.8	1.9	2.8
	1.5	175	42.5	0.63	0.38	2.60	1.9	1.9	2.8
	1.5	175	42.5	0.63	0.38	2.80	2.0	1.9	2.8
	1.5	175	42.5	0.63	0.38	3.0	2.1	1.9	2.8
150-175	0	202	32.5	0.53	0.43	2.4	1.8	1.9	0.0
	0	202	32.5	0.53	0.43	2.60	1.9	1.9	0.0
	0	202	32.5	0.53	0.43	2.80	2.0	1.9	0.0
	0	202	32.5	0.53	0.43	3.0	2.1	1.9	0.0
	1.5	185	32.5	0.53	0.40	2.40	1.8	1.9	0.0
	1.5	185	32.5	0.53	0.40	2.60	1.9	1.9	0.0
	1.5	185	32.5	0.53	0.40	2.80	2.0	1.9	0.0
	1.5	185	32.5	0.53	0.40	3.0	2.1	1.9	0.0
75-100	0	193	32.5	0.53	0.41	2.40	1.8	1.9	2.8
	0	193	32.5	0.53	0.41	2.60	1.9	1.9	2.8
	0	193	32.5	0.53	0.41	2.80	2.0	1.9	2.8
	0	193	32.5	0.53	0.41	3.0	2.1	1.9	2.8
	1.5	175	32.5	0.53	0.37	2.40	1.8	1.9	2.8
	1.5	175	32.5	0.53	0.37	2.60	1.9	1.9	2.8
	1.5	175	32.5	0.53	0.37	2.80	2.0	1.9	2.8
	1.5	175	32.5	0.53	0.37	3.0	2.1	1.9	2.8

size of aggregates results in higher efficiency, higher cost of production, and lower strength.

The third stage is the selection of the amount of air bubbles that varied with the environmental conditions. It should be noted that the amount of unintentional and intentional air bubbles in this stage is determined as 1 and 1.5%, respectively. The fourth stage is to select the volume of water that is shown in the flowchart based on ACI-211 tables and the cost parameter that affects the volume. The fifth stage of the mix design is to calculate the water-cement ratio. Considering that the durability of high-performance concretes is very important in this stage, water-binder ratio, instead of water-cement ratio, is obtained using Fig. 4. As shown in this figure, three types of curves are determined for different strengths of cement. If the manner of round-corner and sharp-corner aggregates will be inserting in this curve, the number of curves will increase to 6. However, it is assumed that the aggregate follows the ideal curve (C33 2004). In the sixth stage, the size of the coarse aggregates is calculated depending on fineness modulus and size of the coarse aggregates according to ACI-211. The size of aggregates selected in the second stage and the fineness modulus in this stage is influential. In this regard, it is assumed to calculate this stage and the seventh stage for one size of aggregate, that is, 25. Finally, all the stages should be corrected to perform the humidity correction. It should be noted that the flowchart should be sometimes repeated from the beginning to the end so as to make the final decision. To further clarify the method, the design of a concrete with the strength of 40 MPa is shown in brief in Table 1.

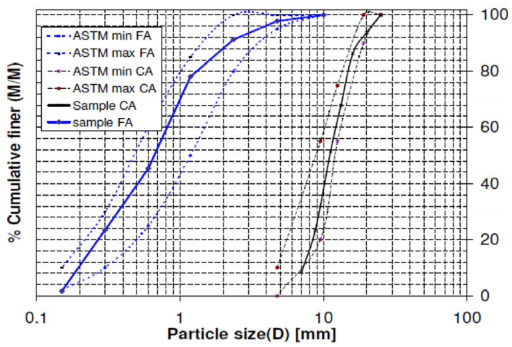

Fig. 5 Gradation curves for CA and FA as per ASTM C33(C33 2004)

Table 2 Mix proportion

Mixture no	Cement (Kg/m^3)	W/C	W/B	W/P	FA/P	CA/P	MS/B (%)	SP500/P (%)
HPC1	30	31	23	0.49	2.1	1.9	3	0.47
HPC2	40	36	32	0.43	1.9	1.8	5	0.65
HPC3	50	42	38	0.38	1.8	1.7	6	0.8
HPC4	55	52	43	0.35	1.7	1.5	7	0.93
HPC5	60	56	47	0.33	1.6	1.4	8	1.04
HPC6	70	65	50	0.31	1.5	1.4	9	1.14

4. Experimental plane

The dynamic model was evaluated by comparing the calculated results with the experimental results. A total of 6 different mixtures for HPC were employed for experimental investigations.

4.1 Materials

(1) Cement (C): The cement used was 53 grades, with strength of 26.50, 33.20, and 53.40 MPa at 3, 7, and28 days, respectively, and specific gravity of 3.14.
(2) Aggregate: Fine aggregate (FA) is from river sand passing 4.75 mm sieve with specific gravity of 2.62 and the fineness modulus of 2.48 were used. Coarse aggregate (CA) is from crushed stone aggregates of 16 mm maximum size. The specific gravity, dry-rodded unit weight and water absorption of the coarse aggregate were 2.71, 1550 kg/m3 and 0.5 by weight of the aggregate, respectively. The sieve analysis is shown in Fig. 5.
(3) High performance water reducing admixture for microsilica concrete (HPWR) (SP500): SP500 is based on sulphonated naphthalene polymers and is supplied as a brown liquid which is instantly dispersible in water.

4.2 Mix proportion

A total of 6 mixes with varying water/powder (W/P) ratio were made as shown in Table 2.

The total cementitious material content was 420–610 kg/m^3. Different water/powder (W/P) ratios (0.49, 0.43, 0.38, 0.35, 0.33 and 0.31) were used to examine 28-day compressive strength and other properties. Compressive strength tests were performed using 150×150×150 mm cubes that were moist cured in a water tank and loaded in a compression machine.

5. Evaluation model

According to Table 1 that shows the mix design of a concrete with the strength of 40 MPa, it can be concluded that many parameters, including the amount of water, cement, slump, fineness of fine aggregates, size of aggregates, the amount of lubricant, micro silica, and the fly ash, directly affect the cost of producing high-performance concretes.

The first column of Table 1 is based on the different slumps determined in the ACI Codes; it should be mentioned that the slump is assumed constant in the mix design based on the conditions of the projects and type of concretes, and then, the mix design is designed. In this project, the slump parameter at baseline was assumed variable, and finally when the lubricant was used, the slump was specified in the range of 150-175, which could affect the cost of production alone. In the second stage, or second column, where the amount of air bubbles of the concrete that affected the amount of slump and water directly was determined, the amount of air bubbles was determined as 0 and 1.5% for all slumps. The third column shows the amount of water required for the concrete in order to reach the desired efficiency and slump based on the amount of air bubbles, and the water parameter varied between the water with and without bubbles depending on the type of slump.

The fourth column is related to the compressive strength of cement. The cement type I follows the three types of compressive strengths of 325, 425, and 525 kg/cm^2 that affect the strength of concrete and amount of W/C or W/B. It also shows that these values increase with an increase in the level of cement strength. The increase in W/C ratio indicates the reduction of cement and Pozzolanic adhesives. Once the amount of W/C, W/B, and W/P was determined, the level of fineness of fine aggregates should be examined.

The eighth column determines the level of fineness modulus of aggregates that changed from 2.4 to 3. These changes have a direct effect on the volume of coarse and fine aggregates, and this in turn affects the cost of concrete production. The superplasticizer parameter was used in the last column in order for the homogenization process to have a level of efficiency and capacity to be used in the high-performance concrete, and all the designs of concrete with strength of 40 MPa would be in the slump range of 150-175. Furthermore, a similar table was applied for concretes with strengths of30, 55, 60, and 70 MPa, and the results are shown in Table 3.

Table 3 shows that the changes in designing the compressive strength dynamically and experimentally follow a favorable trend, as an increase in the level of strength results in an increase in the cost of production.

Fig. 6 analyses the experimental and dynamic data of the mix design and determines their standard deviation. The

Table 3 Result of dynamic and experimental F_c (MPa)

Mixture no	Dynamic mix	Experimental F_c	Cost ($)
HPC1	30	31	23
HPC2	40	36	32
HPC3	50	42	38
HPC4	55	52	43
HPC5	60	56	47
HPC6	70	65	50

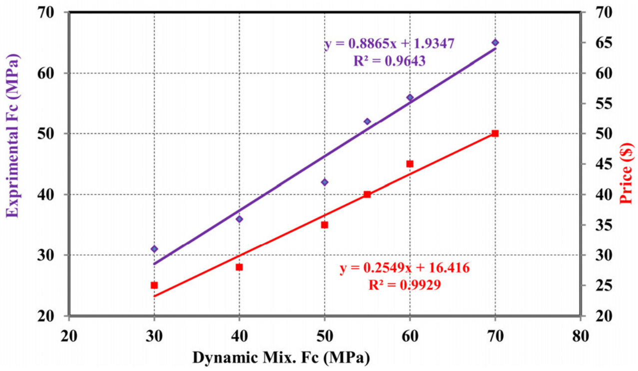

Fig. 6 Comparison of experimental and cost v.s. dynamic

prediction is clearly of high accuracy.

Moreover, Fig. 6 shows the cost of producing this type of concrete with different strengths from 30 to 70 MPa. The increase in strength resulted in an increase in the cost, and both followed the constant approximate gradient of 25%.

6. Conclusions

From the dynamic optimization method which was proposed for high performance concrete (HPC), the following results can be drawn.

(1) Dynamic optimization was applied for the first time in mixture design of concrete. Due to various parameters for HPC such as kind of cement, variation of fineness modulus of aggregate, grading of aggregates that depend on various cost, it is necessary to perform good evaluation, to find at any time, minimum cost of mixture with compressive strength.
(2) The method offered can be used especially when the dependent parameter to compressive strength and other performance are increased.

The results of the experimental investigation show that compressive strength and dynamics optimization are closed. The presented method of dynamic optimization design, allows the rejection of ordinary methods of concrete design where cost of components is effective to define and select concrete type for any concrete ready mix design company.

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