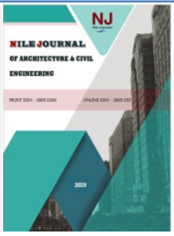
Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 1, Jan. 2024



Prediction of Mix Proportioning of High-Performance Concrete using Harmony Search Algorithms

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Abstract

High-performance concrete is defined as concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. A large number of trial mixes are required to select the desired combination of materials that meets special performance. Therefore, in this paper, using Harmony Search (HS) meta-heuristic algorithms optimization method imitating the music improvisation process where musicians improvise their instruments' pitches searching for a perfect state of harmony. There are three type of Harmony search (Local (LHS), Improved (IHS) and Global (GHS) which were successfully used in different branches of engineering. So, these algorithms are used to predict the quantity of contents of the mixes at different known compressive strength and slump. The results of this research show that, Harmony Search Algorithms is an effective method in prediction of concrete mixes, while comparing the results of the three types of Harmony Search algorithms, it was be found that GHS results is better than IHS better than LHS whither according to min. cost or min. average error.

Key words: High-performance concrete; Heuristics; Harmony search algorithm;; Mixture proportioning; Compressive strength; Workability

1. Introduction

Concrete is the dominant construction material today with an annual worldwide production of over 4.5 billion metric tons [1]. Due to the escalation of both wages and material prices in recent years, many people involved in the construction industry have expressed great concern about technologies and managerial skills to improve construction performance. Many construction technologies have been proposed to improve construction performance, such as high-performance concrete (HPC) is used to achieve high strength and workability while reducing creep and shrinkage and low durability with using water-reducing agent, super plasticizers and pozzolanic materials in the mix designs. High strength concrete (HSC) is a type of HPC concrete with specific strength more than 60MP, which using in the big constructions with using silica fume. Self- compacting concrete (SCC) is the concrete, which is able to flow under its own weight and completely fills, inserts and substantial horizontal and vertical flow of the concrete within the formwork and encapsulate the reinforcement, while maintaining homogeneity and can consolidate without the need for vibration compaction.

High-performance concrete is defined as concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents, normal mixing, placing or curing practices. Ever since the term high-performance concrete was introduced into the industry, it had widely used in large-scale concrete construction that demands high strength, high flow-ability, and high durability. To obtain such performances that cannot be obtained from conventional concrete or by the current method. Engineers and constructors all over the world are finding that using high performance concrete allows them to build more serviceable structures at comparable cost. High-performance concrete is being used for structures in aggressive environments: marine structures, highway bridges, pavements, nuclear structures, tunnels and precast units [2, 3]. The water-to-solid (W/S) weight ratio is known to have the significant influence on the volume stability of concrete. To achieve higher workability, a larger amount of water will be required, thus calling for higher cement content. Such mixture proportion will induce risks of concrete creep. Large-scale deformation due to autogenously shrinkage will occur when the (W/C) ratio is < 0.42.

Over the last four decades, a large number of algorithms have been developed to solve various engineering optimization problems. Most of these algorithms are based on numerical linear and nonlinear programming methods that require substantial gradient information and usually seek to improve the solution in the neighborhood of a starting point. These numerical optimization algorithms provide a useful strategy to obtain the global optimum in simple and ideal models. Many real-world engineering optimization problems, however, are very complex in nature and quite difficult to solve using these algorithms. If there is more than one local optimum in the problem, the result may depend on the selection of an initial point, and the obtained optimal solution may not necessarily be the global optimum. Furthermore, the gradient search may become difficult and unstable when the objective function and constraints have multiple or sharp peaks. The common factor in meta-heuristic algorithms is that they combine rules and randomness to imitate natural phenomena. These phenomena include the biological evolutionary process (e.g., the evolutionary algorithm proposed by Fogel et al. [4], De Jong [5], and Koza [6] and the genetic algorithm (GA) proposed by Holland [7] and Goldberg [8]).

Recently, Geem et al. [9] developed a new harmony search (HS) meta-heuristic algorithm that was conceptualized using the musical process of searching for a perfect state of harmony. The harmony in music is analogous to the optimization solution vector, and the musician's improvisations are analogous to local and global search schemes in optimization techniques. The HS algorithm does not require initial values for the decision variables. Furthermore, instead of a gradient search, the HS algorithm uses a stochastic random search that is based on the harmony memory considering rate and the pitch adjusting rate (defined in harmony search meta-heuristic algorithm section) so that derivative information is unnecessary. Compared to earlier meta-heuristic optimization algorithms, the HS algorithm imposes fewer mathematical requirements and can be easily adopted for various types of engineering optimization problems.

Meta-heuristic Harmony Search algorithm has been successfully used in many engineering branches such as project management, structure design, steel design and roads [10- 12]. However, it's not used optimally in concrete mix design before, so it will be studied in this thesis trying to achieve a concrete with special properties to minimize the trials in the laboratory and with minimum cost of the mixes. A meta-heuristic algorithm, mimicking the improvisation process of music players, has been recently developed and named Harmony Search (HS). Harmony Search algorithm had been very successful in a wide variety of optimization problems, presenting several advantages with respect to traditional optimization techniques such as the following: (a) HS algorithm imposes fewer mathematical requirements and does not require initial value settings of the decision variables. (b) As the HS algorithm uses stochastic random searches, derivative information is also unnecessary. (c) The HS algorithm generates a new vector, after considering all of the existing vectors, whereas the genetic algorithm (GA) only considers the two parent vectors. These features increase the flexibility of the HS algorithm and produce better solutions [13].

The traditional Harmony Search was known as Local Harmony Search (LHS). In order to improve the fine-tuning characteristic of HS algorithm, Improved Harmony Search (IHS) employs a new method that enhances fine-tuning characteristic and convergence rate of harmony search. The IHS algorithm has the power of the HS algorithm with the fine-tuning feature of mathematical techniques and can outperform either one individually [14, 15]. The IHS was developed to global-best harmony search (GHS), modifies the pitch adjustment step of the HS such that the new harmony can mimic the best harmony in the HM. Intuitively, this modification allows the GHS to work efficiently on both continuous and discrete problems [16].

2. The High-Performance Concrete and Its Most Effective Independent Parameters

High-performance concrete is designed to give optimized performance characteristics for a given set of materials, usage, and exposure conditions, consistent with strength, workability, service life, and durability. Engineers and constructors all over the world are finding that using high performance concrete allows them to build more serviceable structures at comparable cost. High-performance concrete is being used for structures in aggressive environments: marine structures, highway bridges and pavements, nuclear structures, tunnels, precast units, etc. [17, 18]. The major difference between conventional concrete and high-performance concrete is essentially the use of chemical and mineral admixtures. The use of chemical admixtures reduces the water content, thereby at the same time increase the workability. Mineral admixtures, also called as cement replacement materials such as silica fume and fly ash, which was used to increase the compressive strength. Compressive strength and slump are very important characteristics in the design process of concrete. The main independent parameters, which must be considered as factors affecting compressive strength and slump are water to binder ratio, water content, sand to aggregate ratio, silica fume ratio or fly ash ratio, air entraining content and super-plasticizer content.

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2.1 The main fresh and hardened properties of concrete

There are several fresh and hardened tests but the slump test is the most common method of assessing workability of fresh concrete on site and the compressive strength is considering as the most important one strengths properties of hardened concrete.

2.1.1 Slump as Fresh Concrete Properties

The En 206 and additional tests occur in other national stander such as the BS 1881:PT102, and many other standers, slump test is the most common method of assessing workability of fresh concrete on site. It is suitable for concrete of a medium workability when substantial compaction is still required. Slump is a measure of consistency, or relative ability of the concrete to flow. Slump is normally measured by filling an "Abrams cone" with a sample from a fresh batch of concrete.

2.1.2 Compressive Strength as Hardened Concrete Properties

The most common test preformed on concrete is for compressive strength, which enables engineers to assess the strength of a concrete sample and its performance under actual loading, as opposed to the design loading Furthermore, any deterioration, from chemical action, weathering, fatigue or excessive loading, can be precisely measured. It is taken as a base for specifications and quality control. Concrete usually attains about 90% of its compressive strength after 28 days. So, 28 days compressive strength is the earlier age can accurately represent the real value of the compressive strength of 150 mm size cubes tested (f_{ck}).

2.2 Considered factors affecting compressive strength and slump for determination of the independent variables:

The factors affecting compressive strength and slump must be considered to determine the independent variables of the fitness functions in order to determine mix proportions by applying a Harmony Search to the fitness functions composed of selected independent variables. The factors affecting compressive strength are water to binder ratio (W/B, %), water content (W, kg/m3), fine aggregate ratio (S/A, %), replacement ratio of silica fumes (SF, %), content of air-entraining agent (AE, kg/m3), and super plasticizer (SP, kg/m3) [19].

2.2.1 The effect of (W/B, %) and water content (W, kg/m3) on the compressive strength and the slump

Water combines with the cementations material during a reaction referred to as hydration to create hardened concrete. The weight of the water in the mix (added water plus free moisture on the aggregates) divided by the weight of cementations material forms what is referred to as the water-cementations material ratio (W/C). This characteristic of the concrete mix determines, to a great extent, the overall quality of the concrete relative to its engineering properties such as density, strength, workability. Under standard conditions, an increase in W/C ratio would generally lead to a fall in the concrete strength. This quantity of additional water can offer sufficient moisture to the hydration process to evolve under more or less valid conditions. It would also consist in maintaining workability and compensating at the same time the mixing water lost by evaporation.

2.2.2 The effect of (S/A, %) on compressive strength and slump

Both of the compressive strength and the slump flow increase with an increase in the S/A ratio. Particle packing characteristics may play a significant role on the concrete flow-ability. In a laboratory experiment, with a constant W/B ratio of 0.60, when the coarse/fine aggregate proportion and the cement content of a concrete mixture were progressively raised to increase the slump from 50 to 150 mm, a 12% decrease in the average 7-day compressive strength was observed [20].

2.2.3 The effect of fine material admixture [silica fume (SF) %] on compressive strength and slump

Fine material admixtures are added to concrete as part of the total cementation system. They may be used in addition to or as a partial replacement of portland cement in concrete depending on the properties of the materials and the desired effect on concrete [21]. Fine material admixtures are used to improve a particular concrete property such as workability, strength or comp-activity. Micro-silica is a by product of the production of silicon element or ferro-silicon alloys. Silica metal and alloys are produced in electric furnaces. Nowadays, it has been well known that the use of SF can significantly improve the engineering properties such as strength and mechanical as well as durability of HPC [22]. It has been well known that silica fume has an effect on enhancing the strength of concrete and has been widely used in producing HPC. Compared to normal Portland cement and typical fly ash, silica fume shows particle size distributions that are two orders of magnitude finer. In conclusion, silica fume has an effect on decreasing the workability of high-performance concrete.

2.2.4 The effect of content of chemical admixtures (super plasticizer) on compressive strength on slump

A wide range of chemicals admixture have been developed to enhance the performance of concrete and its engineering properties. These products are usually liquids or powders which are added to the concrete during the batching process. SP is used to reducing the amount of water of convenience needed to place the concrete, thereby, reducing the overall W/B% while maintaining acceptable workability and improvement the concrete strength by reducing the amount of water. So, the addition of SP has a good improving effect on both of the workability as a direct effect and compressive strength as indirect effect by reducing the amount of water.

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2.2.5 Effect of content of air-entraining (ae, kg/m3) on compressive strength and slump

When air voids are incorporated into the system, either as a result of inadequate compaction or through the use of an air-entraining admixture, they have the effect of increasing the porosity and decreasing the strength of the system. It has been observed that the extent of the strength loss as a result of entrained air depends not only on W/B ratio of concrete mixture but also on the cement content. In short, as a first approximation, the strength loss due to entrained air can be related to the general level of concrete strength. At a given W/B ratio, high strength concretes suffer a significant strength loss with increasing amounts of entrained air, whereas low strength concrete tend to suffer only a little strength loss or may actually gain some strength as a result of air entrainment.

2.2.6 The effect of coarse aggregate type on compressive strength and slump

The types of coarse aggregate play a more important role in HSC than NSC. Generally, the compressive strength of the concrete depending on the cohesion force between the mortars with aggregate. In HSC the strength of the aggregate must be bigger than the strength of the concrete to avoid happening cracks in the aggregate under the required force. So the type of the aggregate, its shape, its softness and its surface area are very important parameters especially its type.

3. Harmony search meta-heuristic algorithms

A Harmony Search (HS) meta-heuristic algorithm was derived based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation.

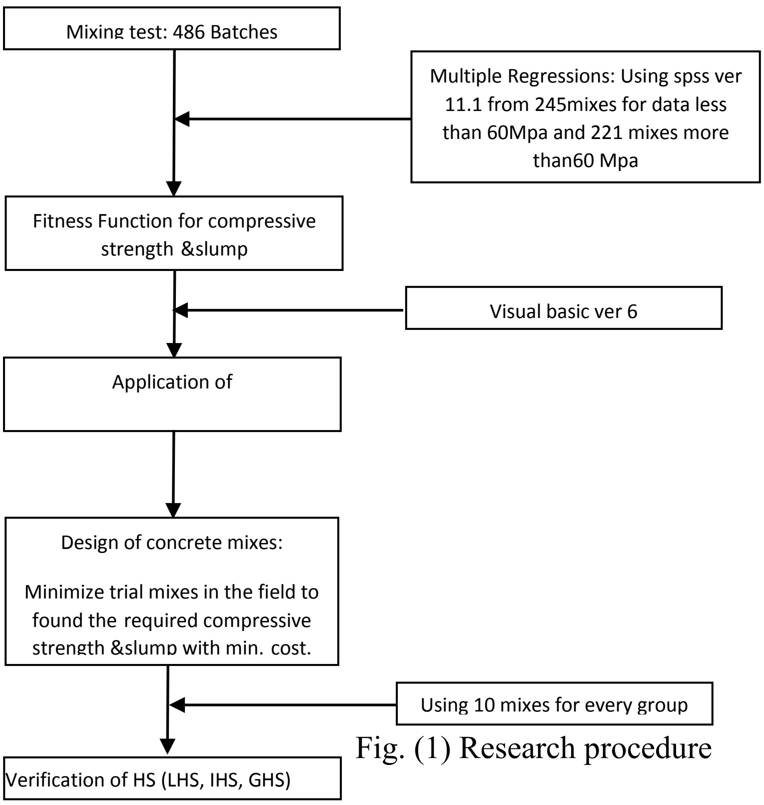

Fig. (1) Research procedure

The harmony quality is enhanced practice after practice, just as the solution quality is enhanced iteration by iteration. The Harmony Search (HS) meta-heuristic algorithm in concrete mix design, which was developed by Geem et al. [9], that was conceptualized using the musical process of searching for a perfect state of harmony. The harmony in music is analogous to the optimization solution vector, and the musician's improvisations are analogous to local, improved, and global search schemes in optimization techniques. The Harmony Search (HS) algorithm does not require initial values for the decision variables.

3.1 Steps of Local Harmony Search Algorithm

(1) Step 1. Initialize The Optimization Problem And Algorithm Parameters:

The concerned problem is to design concrete mixes by Harmony Search with Specific values of both compressive strength and slump so the compressive strength and the slump are considered target objectives, so there are two objective functions must be achieved. The main independent parameters which has a great effect on both of compressive strength and slump are water to binder ratio (W/B)%, water content (W) kg/m3, sand to aggregate ratio (S/A)%, silica-fume (SF)%, air-entraining (AE) kg/m3, and super-plasticizer (SP) kg/m3.

(2) Initialize The Harmony Memory (HM):

Initialize the harmony memory by collecting 486 mixtures from international papers, which consist of cement, water, sand, aggregate, silica-fume, air-entraining, and super-plasticizer only. Every mixture must have its compressive strength with (MPa), which was tested on (15mm) standard cube and slump with (mm). This data will be divided into two groups according to its strength. Ten samples were selected from every group of data randomly by (SPSS) program to test the Harmony Search program), which are located in tables (1), (2). The targets were finding mixes with required compressive strength and slump with minimum cost. The objective functions of both compressive strength and slump for every group were found from the collecting data. The functions of compressive strength and slump were made by (SPSS) program. The Eq. (1), (2) are the objective functions of the data which is less than 60 (MPa) and Eq. (3), (4) are the objective functions of the data which is more than 60 (MPa)

The objective functions of the data which is less than 60 (MPa)

$$f(fcu) = 41.195 - 0.582 * W/B\% + 0.007858 * W + 0.128 * s/a\% + 0.938 * SF - 40.974 * AEA + 1.765 * ca\ type \quad (1)$$

$$f(slump) = -81.956 + 0.02167 * W/B\% + 0.02911 * W + 5.5835 * s/a\% - 3.078 * SF + 13.239 * AEA + 3.255 * SP + 0.138 * ca\ type \quad (2)$$

The objective functions of the data which is greater than 60 (MPa)

$$f(fcu) = 99.549 - 1.423 * W/B\% - 0.0116 * W - 0.272 * s/a\% + 0.793 * SF + 1.522 * ca\ type \quad (3)$$

$$f(slump) = -712.042 + 11.444 * W/B\% + 0.111 * W + 6.664 * s/a\% + 2.355 * SF + 17.405 * SP + 3.539 * ca\ type \quad (4)$$

3. *Step 3. Improvise a new harmony from the harmony memory (HM):*

In Step 3, a New Harmony vector is generated from the harmony memory (HM) based on memory considerations, pitch adjustments, and randomization. For instance, the value of the first design variable ($x_1^{'}$) of the new vector can be chosen from any value in the specified harmony memory (HM) ($x_1^{'1} - x_1^{'HMS}$). Values of the other design variables ($x_2^{'}$, $x_3^{'}$,…., $x_N^{'}$) can be chosen in the same manner. Here, it is possible to choose the new value using the harmony memory considering rate (HMCR) parameter, which varies between 0 and 1. The harmony memory considering rate (HMCR) is the probability of choosing one value from the historic values stored in the harmony memory (HM), and (1- HMCR) is the probability of randomly choosing one feasible value not limited to those stored in the harmony memory (HM) Eq. (5). The Pitch adjusting process is performed only after a value is chosen from the harmony memory (HM) Eq. (6). Every component of the New Harmony vector is examined to determine whether it should be pitch-adjusted. This procedure uses the pitch adjusting rate (PAR) parameter, which is varies between 0 and 1, that sets the rate of adjustment for the pitch chosen from the harmony memory (HM).

$$\text{HMCR decision } x_i^{'} \leftarrow \begin{cases} x_i^{'} \in \{x_i^{1},, x_i^{2}, ...x_i^{HMS}\} & \text{with probability HMCR,} \\ x_i^{'} \in X_i & \text{with probability(1 - HMCR).} \end{cases} \quad (5)$$

$$\text{pitch adjusting decision for } x_i^{'} \leftarrow \begin{cases} \text{Yes} & \text{withprobability} \quad \text{PAR,} \\ \text{No} & \text{withprobability} \quad \text{(1 - PAR).} \end{cases} \quad (6)$$

For local Harmony Search the value of harmony memory considering rate (HMCR) and pitch adjusting rate (PAR) are found by testing the first sample at difference values of HMCR and PAR as in and fined the new variable from Eq. (7). The variables and then found the values of the compressive strength and slump from the equations.

$$x_i^{'} \leftarrow x_i^{'} + \alpha \quad \text{for continuous decision variables} \quad (7)$$

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4. *Step 4. Harmony Memory matrix is updated:*

The input data is sorted and divided into two matrices according to the target compressive strength (f_{cu}), the first matrix is for the data greater than the target f_{cu} and the other for the data less than the target f_{cu}. If the required f_{cu} bigger than the target f_{cu} and less than the biggest value in the first matrix the biggest value in the matrix is changed with the required f_{cu} unless if the required f_{cu} less than the target f_{cu} and bigger than the smallest value in the second matrix the smallest value in the matrix is changed with the required f_{cu} unless refuse the trial. If the required values of compressive strength and slump was in the range of target values of them, the required values are stored in the output matrix. The range of the compressive strength is [$f_{cu\ (target)} \pm 2$ (MPa)] and the range of slump is [$slump_{(target)} \pm 25$ (mm)].

5. *Step 5. Check reaching to the target:*

If the required values of compressive strength and slump were in the ranges of target values of them, the required values are butted in the output matrix, when the range of the compressive strength is [$f_{cu(target)} \pm 2$ Mpa] and the range of slump is [$slump_{(target)} \pm 25$ (mm)]. Then sorting the results according to them cost to find the min. mixtures cost, and again sorted according to the error of all the parameters to find the min. mixtures error.

3.2 Steps of Improved Harmony Search Algorithm (IHS)

The LHS algorithm uses fixed value for both pitch adjusting rate (PAR) and the bandwidth (*bw*). In the LHS method pitch adjusting rate (PAR) and the bandwidth (*bw*) values adjusted in initialization step (Step 1) and cannot be changed during new generations. The main drawback of this method appears in the number of iterations the algorithm needs to find an optimal solution. Small PAR values with large *bw* values can cause to poor performance of the algorithm and considerable increase in iterations needed to find optimum solution. Although small *bw* values in final generations increase the fine-tuning of solution vectors, but in early generations *bw* must take a bigger value to enforce the algorithm to increase the diversity of solution vectors. Furthermore, large PAR values with small *bw* values usually cause the improvement of best solutions in final generations which algorithm converged to optimal solution vector. The key difference between IHS and traditional HS method is in the way of adjusting pitch adjusting rate (PAR) and the bandwidth (*bw*) in step 3. To improve the performance of the HS algorithm and eliminate the drawbacks lies with fixed values of PAR and the *bw*, IHS algorithm uses variables PAR and the *bw* in improvisation step (Step 3). PAR and the *bw* change dynamically with generation number and calculated from Eq. (8), (9) instead of constant values. So, only HMCR must be tested.

$$PAR_{(gn)} = PAR_{\min} + \frac{(PAR_{MAX} - PAR_{\min})}{NI} \times gn \tag{8}$$

$$bw_{(gn)} = bw_{\max} \cdot \exp\left(\frac{Ln(\frac{bw_{\min}}{bw_{\max}})}{NI} \cdot gn \right) \tag{9}$$

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3.3 Steps of Global Harmony Search Algorithm (GHS)

The global-best Harmony Search (GHS) has exactly the same steps as the improved Harmony Search (IHS) with the exception that Step 3 has different in pitch adjustment probability (PAR) only. Although, the value of PAR is the same as IHS calculated from Eq. (8), but the difference in the means of the probability is choose the best value of the variable $x_i^{'} \leftarrow x_k^{best}$, which considered one of the parameters of the best value of the target instead of ($x_i^{'} \leftarrow x_i^{'} + \mathrm{b}w_{\ (gn)} * \mathrm{u}(-1,1)$).

4. Material Properties for All the Collecting Mixes

All the collected mixes were made with Portland cement in accordance with ASTM type I. A water reducer super-plasticizer was used to keep the water to binder (W/B) ratio of concrete at a very low level. An air-entraining agent was used. A fine material such as silica fume and lime stone powder which is used in addition to or as a partial replacement of Portland cement in concrete to produce denser concrete with higher compressive strength, were used. Viscosity enhancing agent was used to improve the flowability and in the same time enhanced the stability (viscosity) of concrete. The mix proportions which have a compressive strength less than 60 MPa are collected. The W/B varies between 0.15 and 0.667, the range of water content (W) is 113.5–256 kg/m^3, and the amount of sand used varies from 24% to 60% of the total aggregate, and the amount of silica fume used varies from 0% to 25% of the total binder, the air-entraining agent 0.036–3.6 kg/m^3, and the content of super-plasticizer is 0–66 kg/m^3. The mix proportions which have a compressive strength more than 80 MPa are presented in Table 3.2. The W/B varies between 0.15 and 0.667, the range of water content (W) is 113.5–256 kg/m^3, and the amount of sand used varies from 24% to 60% of the total aggregate, and the amount of silica fume used varies from 0% to 25% of the total binder, and the amount of fly ash used varies from 0% to 40% of the total binder, the air-entraining agent 0.036–3.6 kg/m^3, and the content of super-plasticizer is 0–66 kg/m^3.

Table (1) part of data less than 60 MPa

No	FC (MPa)	SLUMP (mm)	W/B %	W (Kg/m^3)	S/A %	SF %	AE (Kg/m^3)	Sp (Kg/m^3)	CA_TYPES
1	59.17	200	30	160	46	0	0.069	8	C.granite(2.7)
2	55.00	210	30	170	47	0	0.074	8.5	C.granite(2.7)
3	54.17	225	30	170	44	0	0.074	8.5	C.granite(2.7)
4	50.83	220	30	180	45	0	0.078	7.5	C.granite(2.7)
5	51.67	210	30	180	42	0	0.078	7.5	C.granite(2.7)
6	50.83	225	30	180	38	0	0.078	7.5	C.granite(2.7)
7	52.50	145	35	160	51	0	0.059	5.71	C.granite(2.7)
8	52.50	175	35	160	48	0	0.059	5.71	C.granite(2.7)
9	52.50	185	35	160	45	0	0.059	5.71	C.granite(2.7)
10	49.17	195	35	170	46	0	0.063	4.86	C.granite(2.7)
11	47.50	220	35	170	43	0	0.063	4.86	C.granite(2.7)
12	45.83	195	35	180	48	0	0.067	3.86	C.granite(2.7)
13	46.67	150	35	180	44	0	0.067	3.86	C.granite(2.7)
14	44.17	190	35	180	41	0	0.067	3.86	C.granite(2.7)

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15	42.50	170	40	160	52	0	0.04	4	C.granite(2.7)
16	41.67	230	40	160	46	0	0.04	4	C.granite(2.7)
17	40.83	205	40	170	51	0	0.043	2.13	C.granite(2.7)
18	39.17	190	40	170	48	0	0.043	2.13	C.granite(2.7)
19	39.17	170	40	170	45	0	0.043	2.13	C.granite(2.7)
20	37.50	210	40	180	46	0	0.045	2.25	C.granite(2.7)
21	36.67	220	40	180	43	0	0.045	2.25	C.granite(2.7)
22	39.17	180	45	160	53	0	0.036	3.56	C.granite(2.7)
23	37.50	160	45	160	50	0	0.036	3.56	C.granite(2.7)
24	36.67	120	45	160	47	0	0.036	3.56	C.granite(2.7)
25	38.33	175	45	170	52	0	0.038	1.89	C.granite(2.7)
26	35.83	190	45	170	49	0	0.038	1.89	C.granite(2.7)
27	35.83	200	45	170	46	0	0.038	1.89	C.granite(2.7)
28	35.00	230	45	180	51	0	0.04	2	C.granite(2.7)
29	35.00	170	45	180	47	0	0.04	2	C.granite(2.7)
30	35.83	175	45	180	44	0	0.04	2	C.granite(2.7)
31	56.67	143	33	167	33	0	0	7.59	gravel(2.68)
32	65.33	112	33	157	33	10	0	7.25	gravel(2.68)
33	44.50	96	40	200	33	0	0	0	gravel(2.68)
34	54.50	130	36	180	33	5	0	0	gravel(2.68)
35	62.17	203	32	160	33	10	0	8	gravel(2.68)
36	51.58	225	30	162	45	0	0	13.5	C.lime st(2.7)
37	55.17	200	30	135	41	7.5	0	4.55	granite(2.69)
38	43.08	240	30	136	40	7.5	0	7.1	granite(2.69)
39	52.83	60	35	173	60	0	0	2	C.lime st(2.7)
40	37.08	20	50	177	60	0	0	0	C.lime st(2.7)

Table (2) part of data more than 60 MPa

No	FC (MPa)	SLUMP (mm)	W/B %	W (Kg/m^3)	S/A %	SF %	Sp (Kg/m^3)	CA_TYPES
1	102	200	18	140	35	20	32.1	C.granite(2.7)
2	103	190	18	140	35	25	36.5	C.granite(2.7)
3	96	220	20	145	35	25	26.1	C.granite(2.7)
4	94	215	18	145	35	15	27.7	C.granite(2.7)
5	97	220	18	145	35	20	28.7	C.granite(2.7)
6	99	210	18	145	35	25	28.7	C.granite(2.7)
7	91	220	18	150	35	15	28.2	C.granite(2.7)
8	96	200	18	150	35	20	33.9	C.granite(2.7)
9	88	210	20	140	35	15	21.9	C.granite(2.7)
10	91	185	20	140	35	20	21.4	C.granite(2.7)
11	99	210	20	140	35	25	31.3	C.granite(2.7)
12	93	190	20	145	37	10	19.3	C.granite(2.7)
13	98	190	20	145	37	20	22.5	C.granite(2.7)
14	87	205	20	145	35	15	20.9	C.granite(2.7)
15	89	210	20	145	35	20	20.9	C.granite(2.7)
16	88	190	20	150	37	15	18.1	C.granite(2.7)
17	88	185	20	150	37	20	19.5	C.granite(2.7)
18	88	210	20	150	35	15	20.9	C.granite(2.7)
19	93	190	20	150	35	25	28.7	C.granite(2.7)
20	86	205	20	155	37	10	18.1	C.granite(2.7)
21	87	190	20	155	37	15	18.6	C.granite(2.7)
22	88	200	20	155	37	20	21.0	C.granite(2.7)
23	87	210	22	140	35	15	16.5	C.granite(2.7)

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24	90	200	22	140	35	20	21.4	C.granite(2.7)
25	97	210	22	140	35	25	21.9	C.granite(2.7)
26	86	200	22	145	35	15	19.3	C.granite(2.7)
27	88	220	22	145	35	20	20.9	C.granite(2.7)
28	85	210	22	150	35	15	23.0	C.granite(2.7)
29	89	220	22	150	35	20	20.9	C.granite(2.7)
30	90	220	22	150	35	25	26.1	C.granite(2.7)
31	87	210	23	145	37	10	16.1	C.granite(2.7)
32	88	210	23	145	37	15	15.1	C.granite(2.7)
33	89	200	23	145	37	20	21.9	C.granite(2.7)
34	86	205	23	150	37	10	14.6	C.granite(2.7)
35	73	245	27	160	39	10	13.8	C.granite(2.7)
36	86	200	23	155	39	10	18.8	C.granite(2.7)
37	85	210	23	155	39	15	18.3	C.granite(2.7)
38	86	200	23	155	37	15	14.6	C.granite(2.7)
39	83	190	23	155	37	20	13.7	C.granite(2.7)
40	78	230	23	160	39	5	16.8	C.granite(2.7)

Table (3) Samples less than 60 MPa

No	Fc (MPa)	Slump (mm)	W/B (%)	W (Kg/m^3)	S/A (%)	Sf %	a/e (Kg/m^3)	Sp (Kg/m^3)	CA_TYPE	cost
1	50	150	30	140	41	5	0	4.8	R.siliceous gravel(2.69)	377.4
2	42	168	30	180	40	0	0	5.04	C.gravel(2.68)	365.52
3	44	200	41.5	190	46	0	0.04	5.75	Quartzite(2.65)	298.28
4	37	190	45	180	46	0	0.115	2.25	Granitic gneiss gravel(2.69)	229.25
5	30	115	55	210	32.5	0	0	2	Dolomite(2.64)	216.91
6	59.5	134	34	168	35	7.5	0	9.5	Granite(2.66)	500.26
7	47.5	130	30	155	37.5	7.5	0	5.64	Gravel(2.65)	467.28
8	54.5	125	36	170	33	5	0.104	8.5	C.granite(2.7)	429.25
9	40	100	45	210	30	0	0	2.4	C.basalt(2.75)	264.53
10	35.4	105	46	172	32	0	0	1.2	C.dolomite(2.68)	202.56

Table (4) Samples more than 60 MPa

No	Fc (MPa)	Slump (mm)	W/B (%)	W (Kg/m^3)	S/A (%)	Sf %	Sp (Kg/m^3)	CA_TYPE	cost
11	76	170	28.82	155	36	8.5	12.9	Basalt (2.98)	596.61
12	86	200	28	160	36	18	13.6	C.granite(2.7)	822.51
13	68	113	26	145	40	10	11.5	C.gravel(2.68)	623.54
14	62	100	29	155	38	16	9.5	Lime st(2.65)	690.05
15	83.00	250	26	136	35	16.75	19.2	Quartzite(2.65)	817.8
16	72.00	200	28	142	36	10	16.25	C.dolomite(2.68)	650.16
17	65.00	150	31	150	42.50	8.00	8.9	Granitic gneiss gravel(2.69)	493.12
18	90.00	180	23	125	39	10	15.5	Adensite(2.89)	663.5
19	79.00	200	25.5	155	41.5	8	14.5	Granite(2.66)	662.6
20	100.00	200	20	117	35	15	19	Tard rock(3.14)	846.6

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5. The values of the parameters of HS

The values of HMCR, PAR, *bw* and no. of iterations were tested and found for every type of HS. They are shown in table (5)

Table (5) The values of the parameters of HS

	LHS	IHS	GHS
HMCR	0.95	0.8	0.9
PAR	0.05	0.01→0.99	0.01→0.99
$bw_{W/B}$	5	1→5	
bw_{W}	10	1→10	
$bw_{s/a}$	1	0.1→1	
bw_{SF}	10	1→10	
bw_{AEA}	0.01	0.001→0.01	
bw_{SP}	2	0.1→2	
No. iterations*trials	1000*10	1000*10	1000*100

6. The results & discussion

After introducing specific compressive strength and slump, the Harmony Search algorithm programs for the mix proportioning of high-performance concrete were performed to find mix proportions with a minimum cost and average error.

6.1 The Parameters Sensitivity

The spread of values for each of the input parameters will be indicated from L (low) to H (high) values. The averages for the data are indicated by ‘AV’, while ‘ML’ and ‘MH’ represent points that are midway between L and AV and AV and H, respectively. The sensitivity analyses were initially performed by varying the input parameter of interest from its L to H values through its ML, AV and MH values, while keeping all other parameters at their average values and then found the fitting curve for every parameter. The results from these analyses for selected input parameters are shown in Figs.

6.1.1 The parameters sensitivity effect on the compressive strength behavior

The Compressive strength will be calculated for every parameter at every level. The results will be drawn in Figs. (2) and (3) for data less than and more than 60 MPa, respectively.

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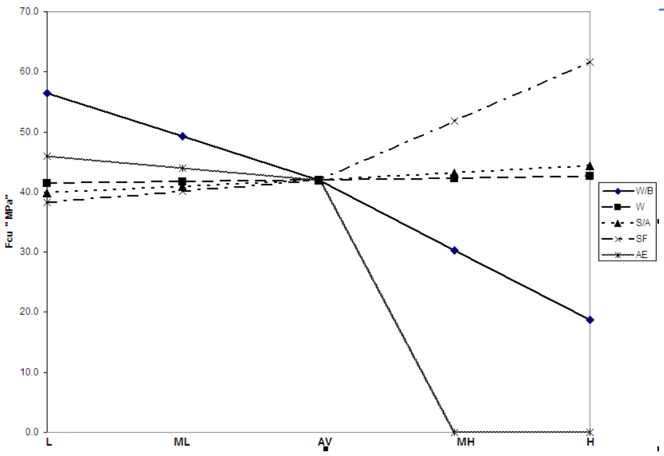

Fig. (2) Strength vs. input parameter levels for the data less than (60 MPa)

We see from Fig. (2) that the parameters were arranged according to its sensitivity. W/B% has the most sensitivity along all the levels. AE quantity don't have a big effect on the strength from the beginning to the average but when it increases more than average it makes a big drop in the strength. SF% has no significant effect when it is less than average (which is equal 5%) but it has a good effect on strength when it increases more than this value. Both of W quantity and S/A% have no significant effect on the strength.

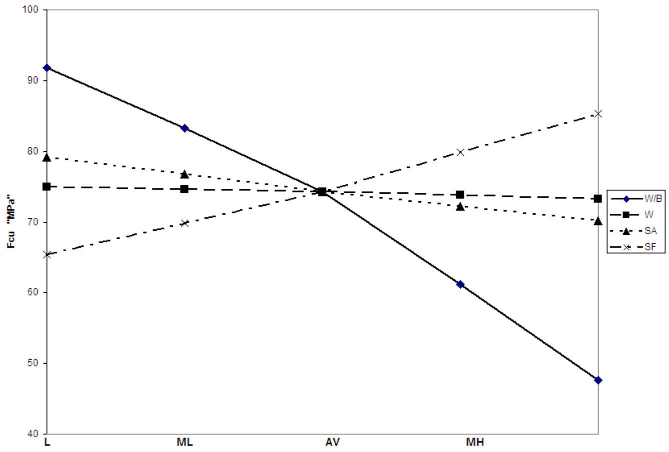

Fig. (3) Strength vs. input parameter levels for the data more than (60 MPa)

One can observe from Fig. (3) that the parameters are arranged according to its sensitivity W/B%, SF%, S/A and W quantity, respectively.

6.1.2 The Parameters Sensitivity Effect on The Slump Behavior

The slump will be calculated for every parameter at every level. The results will be drawn in Figs. (4) and (5) for data less than and more than 60 MPa, respectively.

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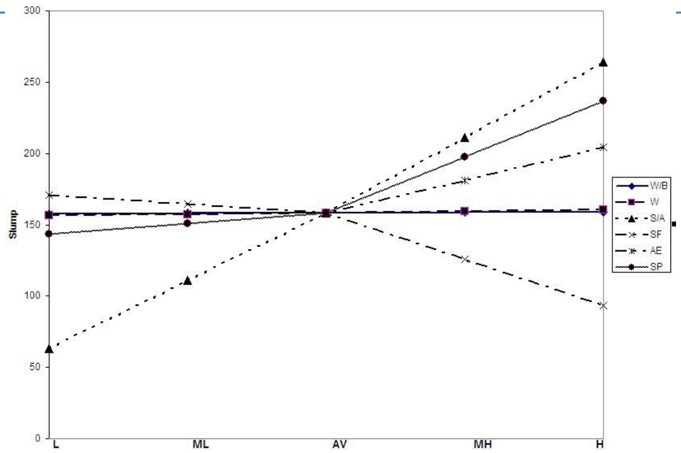

Fig. (4) Slump vs. input parameter levels for the data less than (60 MPa)

We see from Fig. (4) that the parameters were arranged according to its sensitivity. S/A% has the most sensitivity along all the levels. SP quantity, SF% and AE quantity have not a big effect on the slump from the beginning to the average but when it increases more than average it makes a big effect in the slump behavior. Both of W quantity and W/B% have no significant effect on the slump according to them very low agent in the equation of the slump.

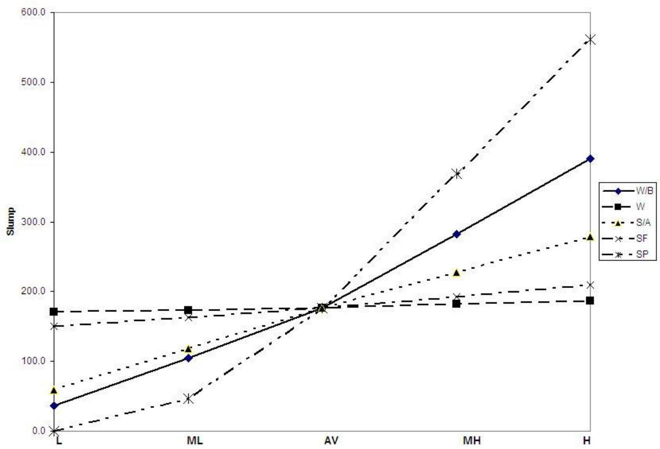

Fig. (5) Slump vs. input parameter levels for the data more than (60 MPa)

We see from Fig. (5) that the parameters were arranged according to its sensitivity. SP quantity has the most sensitivity along all the levels. W/B% is considered the second parameters along all the levels. S/A% is considered the 3rd parameters along all the levels. Both of SF% and W quantity have no significant effect on the slump according.

6.2 Comparison between The Results of different types of Harmony Search algorithms

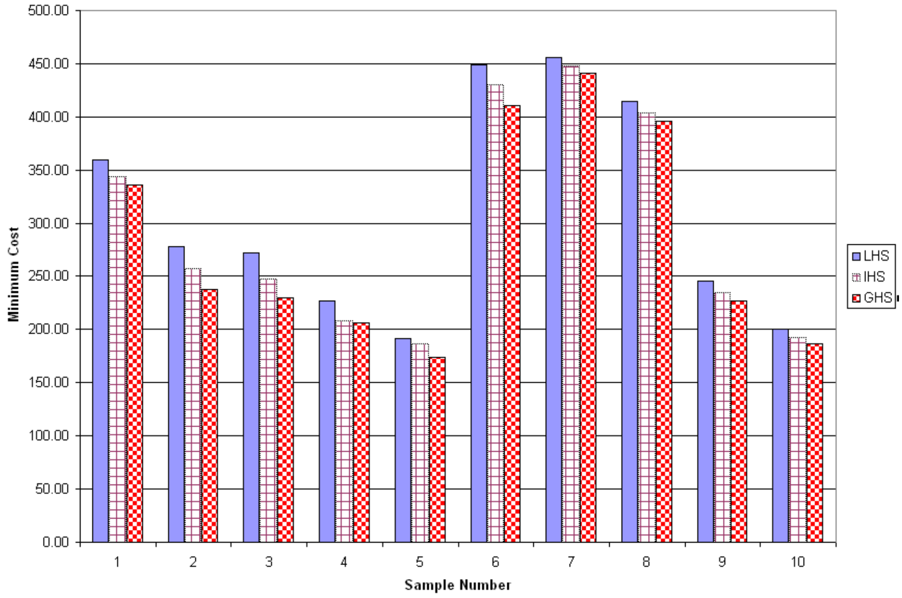

Fig. (6) Relation between Sample number and Min. Cost for LHS, IHS and GHS for a strength less than 60 MPa

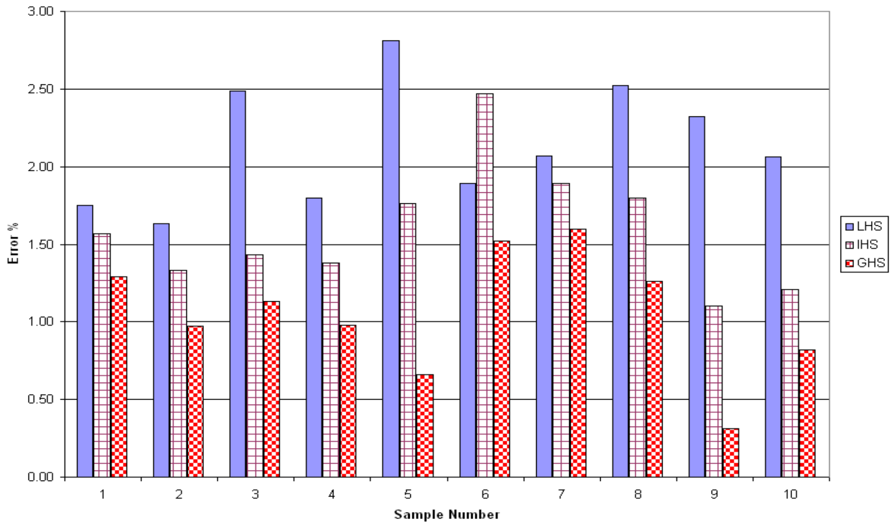

Fig. (7) Relation between Sample number and Min. Error for LHS, IHS and GHS for a strength less than 60 MPa

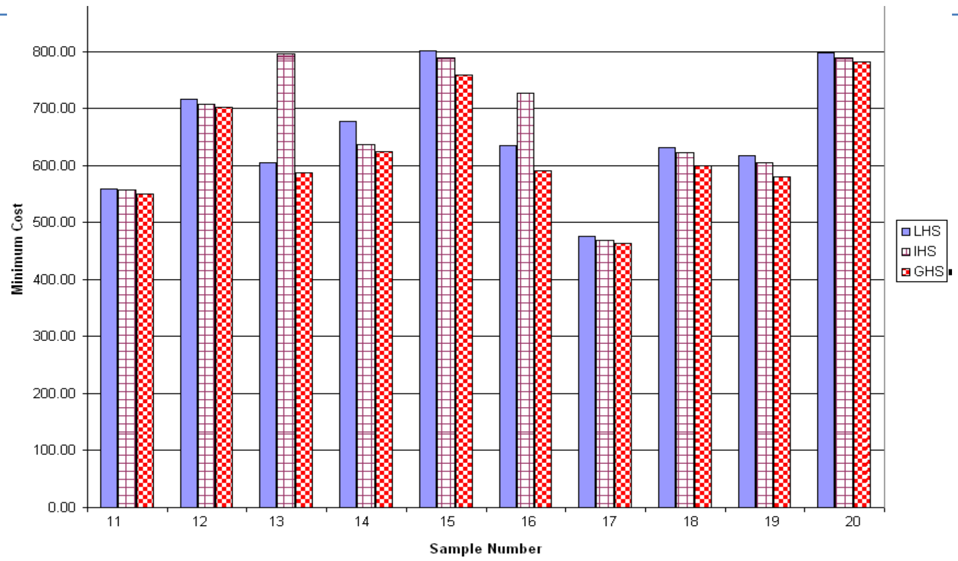

Fig. (8) Relation between Sample number and Min. Cost for LHS, IHS and GHS for a strength more than 60 MPa

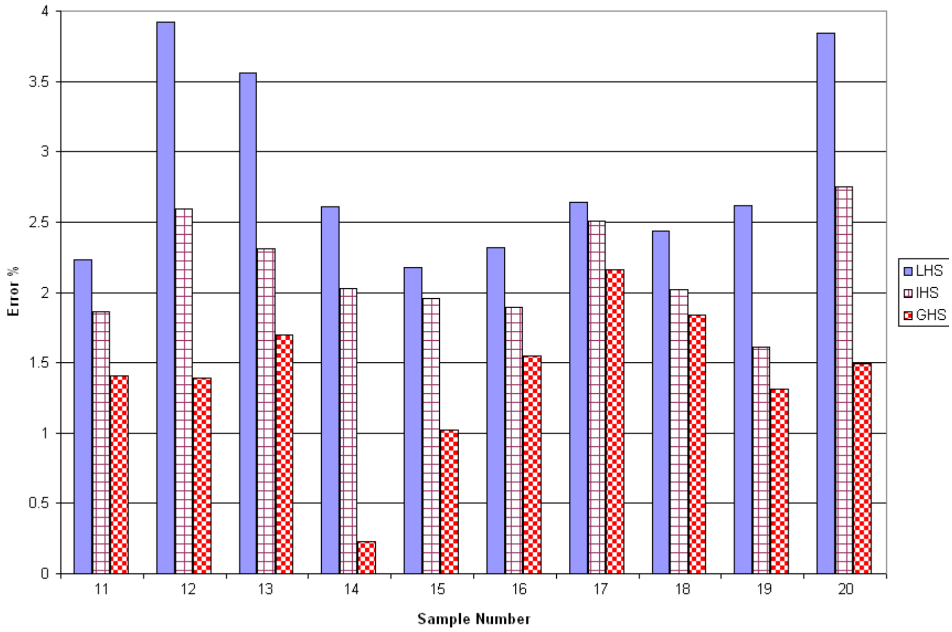

Fig. (9) Relation between Sample number and Min. Error for LHS, IHS and GHS for a strength more than 60 MPa

From all the previous figures, one can easily realize that GHS is the most effective algorithm in achieving minimum cost and minimum average error for both cases of strength, less than 60 MPa and more than 60 MPa. GHS is then followed by IHS and finally, LHS.

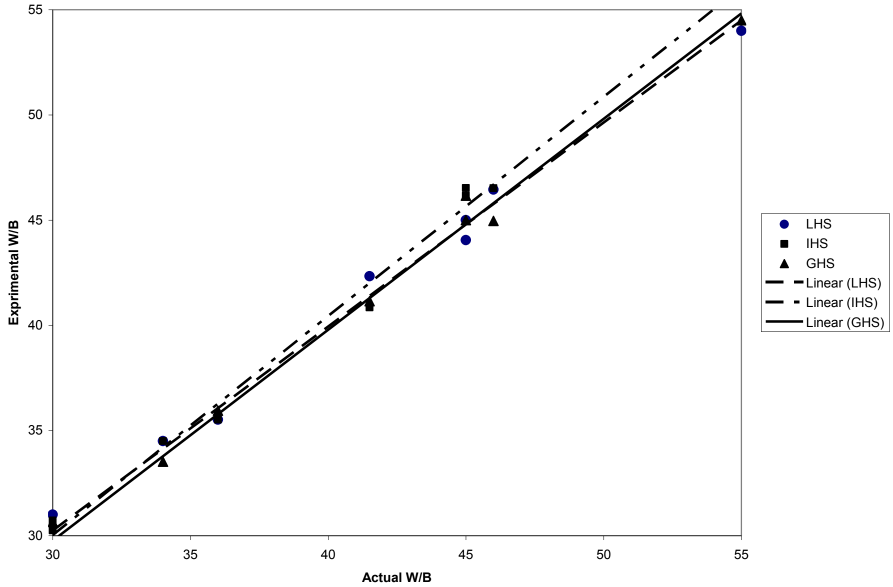

Fig. (10) Fitting curve between actual and experimental W/B for strength less than 60 MPa

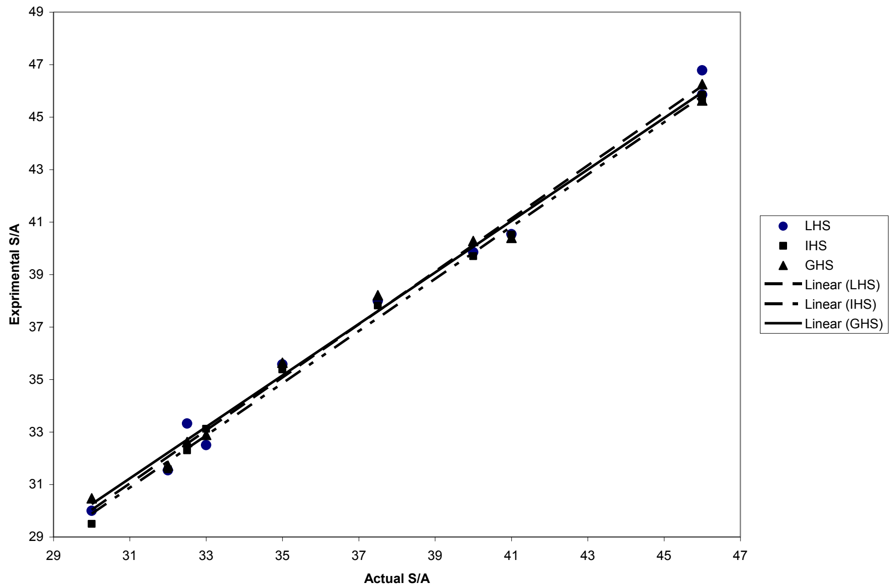

Fig. (11) Fitting curve between actual and experimental S/A for strength less than 60 MPa

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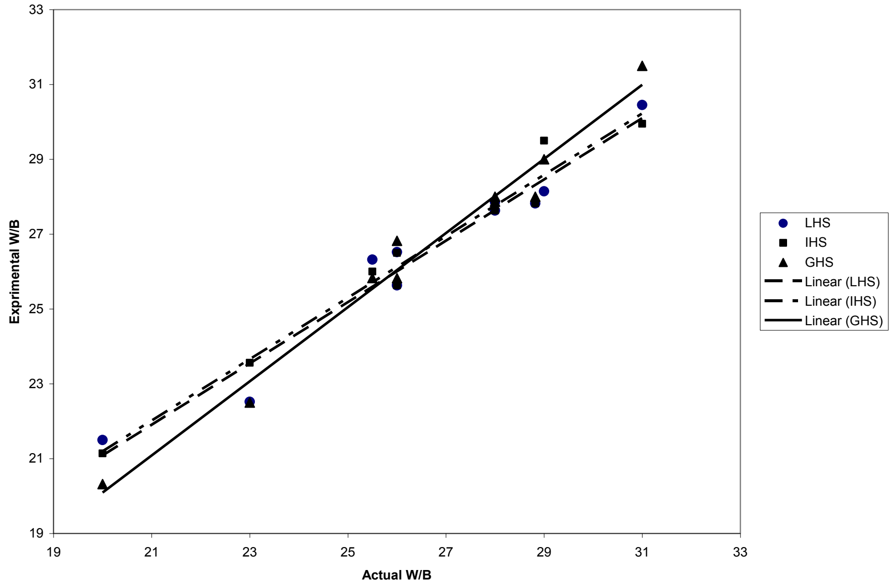

Fig. (12) Fitting curve between actual and experimental W/B for strength more than 60 MPa

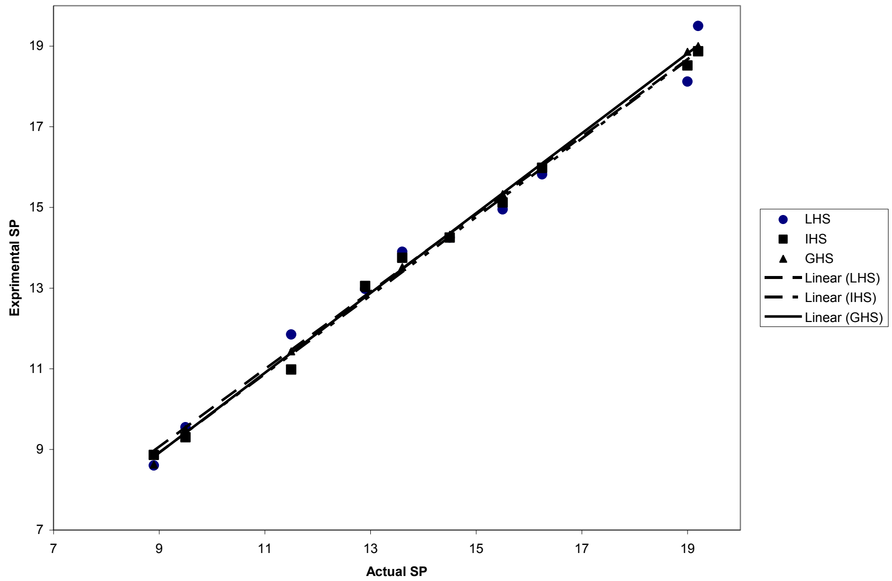

Fig. (13) Fitting curve between actual and experimental SP for strength more than 60 MPa

The previous figures show that the fitting curve for GHS is more accurate than the other curves as it achieves a least square error in each case.

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6.3 Effect of achieving one optimum on the other

6.3.1 Strength less than 60 MPa

In LHS, the average error ranges between 1.63% and 2.81%. If the minimum cost is achieved, the average error ranges is changed to be between 2.35% and 15.25%. The cost ranges between 191.18 pounds and 449.19 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 204.94 pounds and 491.18 pounds. In IHS, the average error ranges between 1.21% and 1.89%. If the minimum cost is achieved, the average error ranges is changed to be between 7.89% and 18.81%. The cost ranges between 186.16 pounds and 448.15 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 204.3 pounds and 498.61 pounds. In GHS, the average error ranges between 0.31% and 1.6%. If the minimum cost is achieved, the average error ranges is changed to be between 6.74% and 22.64%. The cost ranges between 173.68 pounds and 440.74 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 205.01 pounds and 499.71 pounds.

6.3.2 Strength more than 60MPa

In LHS, the average error ranges between 2.18% and 3.92%. If the minimum cost is achieved, the average error ranges is changed to be between 2.7% and 16.08%. The cost ranges between 476.4 pounds and 801.3 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 602.9 pounds and 818.3 pounds. In IHS, the average error ranges between 1.21% and 2.47%. If the minimum cost is achieved, the average error ranges is changed to be between 3.96% and 23.07%. The cost ranges between 490.27 pounds and 789.41 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 469.65 pounds and 804.83 pounds. In GHS, the average error ranges between 0.23% and 2.16%. If the minimum cost is achieved, the average error ranges is changed to be between 3.84% and 14.31%. The cost ranges between 463.2 pounds and 781.79 pounds. On the other hand, if the minimum average error is achieved, the mix cost is changed to be between 494.83 pounds and 839.08 pounds.

The range of errors in W/B, W, s/a, S/F, AE, and SP are 0–4%, 0–4%, 0– 8%, 0%, 0–7%, 4–13%, and 3–10%, respectively. The results show that the errors in W/B, W, s/a, F/A, and S/F are smaller than those of AE and SP. The values of two chemical admixtures are small and have decimal values. Therefore, though the values change on a very small scale, the errors of two chemical admixtures tend to have large values when the errors are expressed in the unit of percentage. Therefore, the errors of chemical admixture are considered to be not so large.

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7. Conclusions

The obtained results show that GHS is the most effective algorithm in achieving minimum cost and minimum average error for both cases of strength, less than 60 MPa and more than 60 MPa. GHS is then followed by IHS and finally, LHS.

7.1 The effective parameters of the compressive strength behavior

For data with strength less than 60 MPa, W/B% has the most sensitivity along all the levels. AE quantity don't have a big effect on the strength from the beginning to the average but when it increases more than average it makes a big drop in the strength. SF% has no significant effect when it is less than average (which is equal 5%) but it has a good effect on strength when it increases more than this value. Both of W quantity and S/A% have no significant effect on the strength. For data with strength more than 60 MPa, the parameters are arranged according to its sensitivity W/B%, SF%, S/A and W quantity, respectively.

7.2 The effective parameters of the slump behavior

For data with strength less than 60 MPa, the parameters were arranged according to its sensitivity. S/A% has the most sensitivity along all the levels. SP quantity, SF% and AE quantity don't have a big effect on the strength from the beginning to the average but when it increases more than average it makes a big effect in the slump behavior. Both of W quantity and W/B% have no significant effect on the slump according to them very low agent in the equation of the slump. For data with strength more than 60 MPa, the parameters were arranged according to its sensitivity. SP quantity has the most sensitivity along all the levels. W/B% is considered the second parameters along all the levels. S/A% is considered the 3d parameters along all the levels. Both of SF% and W quantity have no significant effect on the slump according.

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