International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
SJIF (2024): 6.623

Reliability-Integrated Optimization of Concrete Mix with Variable Aggregates

Rachna Aggarwal

Mukand Lal National College, Yamuna Nagar, Haryana, India.
Email: *raggarwal.math[at]mlncollegeynr.ac.in*

Abstract: ***This study presents an integrated approach combining reliability analysis with deterministic optimization for cost-effective concrete mix design while ensuring the required 28-day compressive strength. The mix constituents—water, cement, fine aggregate, and coarse aggregate—are modeled as random variables following a normal distribution. The objective function minimizes the overall mix cost subject to boundary, ratio, and reliability constraints on compressive strength. Coarse aggregates are categorized into three zones (A, B, and C), and separate optimization models are developed for each. Numerical results are reported across compressive strength targets ranging from 27 MPa to 51 MPa and reliability levels between 0.90000 and 0.99865. The findings indicate that mixes incorporating Zone C aggregates achieve superior cost efficiency and higher reliability compared to those designed with Zone A or Zone B aggregates.***

Keywords: Reliability, optimization, concrete, compressive strength

1. Introduction

Concrete is most important man-made material that is extensively used in construction of highways, dams, bridges, breakwaters, piers and docks, large buildings *etc.* Conventional concrete is a mixture of water, Portland cement and fine and coarse aggregates. Additional components such as chemical and mineral admixtures may be added to the basic mixture to enhance certain properties of fresh or hardened concrete. The process of selecting suitable ingredients for concrete and their relative amount with the objective of producing concrete of required strength, durability and workability as economically as possible is termed as Mix Design. A mix design must fulfill a number of different criteria, such as cost, performance and durability, leading to conflicting requirements to be simultaneously considered. Therefore, the challenge in the design process is how to define the best compromise between contradictory design requirements. Mathematical optimization plays an important role in finding the optimal characteristics leading to greatly improved performance. But, in classical Deterministic Design Optimization (DDO), we assume that there is no variability or uncertainty in the design variables and modeling parameters. However, the information about the input variables is never certain and complete. The uncertainties owe themselves to inherent randomness, limited information, imperfect knowledge and errors. With these uncertainties, deterministic optimization typically yields optimal design that are pushed to the limits of design constraint boundaries; leaving no room for tolerances (uncertainty) in manufacturing imperfections, modeling and design variables. Therefore, deterministic optimal designs that are obtained without taking into account uncertainty are usually unreliable. So, the Reliability has to be integrated with optimization to get realistic results and this optimization is termed as Reliability Based Design Optimization (RBDO). In this context, reliability is the probability of constraint satisfaction. In DDO, reliability is very low (around 0.5) for an active constraint. While RBDO deals with obtaining optimal designs characterized by higher reliability. So, in RBDO problems, there is a trade-off between higher reliability and lowering cost. Several tools have been developed by researchers to solve RBDO problems. (see, *e.g.* [1], [2], [3], [4], [5]). Du and Chen [3] developed Sequential Optimization and Reliability Assessment method (SORA) method for efficient probabilistic design which employs a single loop strategy with a serial of cycles of deterministic optimization and reliability assessment. In the present study, SORA method is used to find optimum mix proportions for minimum cost of concrete with a reliability constraint on the 28 days compressive strength of concrete.

Considerable research activities have been reported in literature on optimization of concrete mix parameters. Sobolev [6] proposed nonlinear regression models for strength of high-performance concrete from the experimental data and provided equations for calculating w/c, for the required compressive strength. Lim *et al.* [7] presented a new design method for high performance concrete mixture using Genetic Algorithms (GA) to provide an appropriate mix proportion under specified requirements. Őzbay *et al.* [8] determined optimum mix proportions for maximum compressive strength of concrete by using Taguchi method and genetic algorithm. Jayaram *et al.* [9] developed elitist genetic algorithm models for the optimization of high- volume fly ash concrete. An enhanced design methodology for optimal mixture proportion of concrete composition with respect to accuracy in the case of using prediction models based on a limited data base was proposed by Lee *et al.* [10]. Baykasoğlu *et al.* [11] followed a two- step approach to optimize High Strength Concrete (HSC) parameters with the first step being the prediction of HSC parameters using regression analysis, neural networks and Gene Expression Programming (GEP) and in the second step a multi-objective optimization model was developed and solved using genetic algorithm. Kumar [12, 13] developed a reliability- based design procedure for concrete mix using the first order second moment approach using Hasofer -Lind method.

2. Reliability Based Design Optimization

2.1 Description of the problem

In reliability- based optimization process, three types of variables are considered: deterministic design variables, random design variables and random design parameters. The design variables that appear in the objective function of the RBDO problem may include deterministic design variables as well as random design variables and the problem is formulated as follows:

$$\begin{aligned} &Minimize : f(\boldsymbol{d}, \boldsymbol{X}, \boldsymbol{P}) \\ &Design\ Variable \quad DV = \{\boldsymbol{d}, \boldsymbol{\mu_x}\} \\ &Subject\ to: \quad Prob\{g_i(\boldsymbol{d}, \boldsymbol{X}, \boldsymbol{P}) \leq 0\} \geq R_i \quad \cdots (1) \end{aligned}$$

Where f is an objective function, $\boldsymbol{d}$ is the vector of deterministic design variables, $\boldsymbol{X}$ is the vector of random design variables, $\boldsymbol{P}$ is the vector of random design parameters. $g_i(\boldsymbol{d}, \boldsymbol{X}, \boldsymbol{P})$ (i =1, 2,. . ., m) are constraint functions, R_i (i=1,2,. . ., m) are desired probabilities of constraints satisfaction, and m is the number of constraints. The design variables are $\boldsymbol{d}$ and the mean $\boldsymbol{\mu_x}$ of the random design variables $\boldsymbol{X}$. In the above probabilistic design model, the design feasibility is formulated as the probability of constraint satisfaction $g_i(\boldsymbol{d}, \boldsymbol{X}, \boldsymbol{P}) \leq 0$ greater than or equal to a desired probability R_i .

2.2 Sequential Optimization and Reliability Assessment (SORA) method

Sequential Optimization and Reliability Assessment (SORA) method developed by Du & Chen [3] employs a single loop strategy with a serial of cycles of deterministic optimization and reliability assessment. The key to SORA method is to shift the boundaries of violated constraints (with low reliability) to the feasible direction based on the reliability information obtained in the previous cycle. In SORA method, RBDO formulated in equation (1) is replaced by deterministic optimization problem given below:

$$\begin{aligned} &Minimize : f(\boldsymbol{d}, \boldsymbol{X}, \boldsymbol{P}) \\ &Design\ Variable \quad DV = \{\boldsymbol{d}, \boldsymbol{\mu_x}\} \\ &Subject\ to: \quad g_i\left(\boldsymbol{d}, \boldsymbol{\mu_x} - \boldsymbol{s}_i^{k+1}, \boldsymbol{P}_{iMPP}^{(k)}\right) \leq 0 \quad (i = 1, 2, \ldots, m) \quad \ldots (2) \end{aligned}$$

Where $\mathbf{s}_i$ is called shift factor with $s_i^{(1)} = 0$ and $s_i^{(k+1)} = \mu_x^{(k)} - X_{iMPP}^{(k)} \quad for\ k \geq 2.$

Several strategies have been implemented within the SORA (Sequential Optimization and Reliability Assessment) framework to enhance the efficiency of Reliability-Based Design Optimization (RBDO):

1) **Percentile-based formulation of probabilistic constraints**: Reliability analysis is conducted only up to the required level corresponding to the target reliability RRR, thereby reducing computational overhead.
2) **Robust inverse Most Probable Point (MPP) search algorithm**: An efficient procedure for identifying the inverse MPP is employed, as detailed in Du et al. [14], ensuring accurate reliability evaluation with minimal iterations.
3) **Sequential cycles of optimization and reliability assessment**: Iterative coupling of deterministic optimization with reliability evaluation facilitates convergence toward a solution that satisfies both performance and reliability requirements.

Collectively, these enhancements render SORA a computationally efficient and robust method for RBDO applications.

3. Reliability based Optimization of Concrete Mix Parameters

3.1 Data used for study

The data for the present work is taken from the experiments conducted by Kumar[7]. He has considered six parameters, namely, water-cementitious material ratio, cementitious content, water content, percentage replacement of cement by fly ash, workability and aggregate of zones in his experiments. The experiments were performed in controlled laboratory conditions. The variation in the values of parameters is given in *Table* 1. One can note from *Table* 1 that coarse aggregates are divided into three zones. The principle characteristics of these zones are given in *Table* 2. The physical properties of fine and coarse aggregates – CA-I, CA-II and CA-III used in the study are provided in *Tables* 3 and 4. A set of 15 cubes for each of mixes so proportioned were cast and tested after 28 days of curing. Thus, an extensive data bank for analyzing compressive strength of concrete has been generated and the same has been used in the present work. Using the data, the mass of different materials in each of the mix designs are calculated using SPSS. Further, unit costs of each material are determined by taking into account the price rates in India. Based on the prices, cost of 1m^3 of concrete is calculated for each mixture.

Table 1: Variation in parameters

Water cementitious material ratio	0.42-0.55
Cementitious content	350-475 kg/m^3@25 kg/m^3
Water content	180-230 kg/m^3@10 kg/m^3
Percentage replacement of cement by fly ash	0 and 15%
Workability	Medium and High
Aggregate zones	A, B, C

Table 2: Zones of coarse aggregates

Zone	Percentage passing 20 mm sieve and retained on 10 mm sieve (CA –I)	Percentage passing 10 mm sieve and retained on 4.75 mm sieve (CA –II)	Percentage passing 4.75 mm sieve and retained on 2.36 mm sieve (CA –III)	Fineness Modulus
A	67	33	-	6.67
B	50	50	-	6.50
C	-	50	50	6.50

Table 3: Physical properties of fine aggregates

S. No.	*Property*	*Observed values*
1.	Unit mass (compact)	1,680 kg/m^3
2.	Unit mass (loose)	1,590 kg/m^3
3.	Specific gravity (oven-dry basis)	2.54
4.	Percentage voids (compact)	33.7 percent
5.	Percentage voids (loose)	37.4 percent
6.	Percentage absorption	0.5 percent
7.	Fineness modulus	2.09

Table 4: Physical properties of coarse aggregates

S. No.	*Property*	*Observed values*		
		CA - I	*CA - II*	*CA - III*
1.	Unit mass (compact)	1,580 kg/m^3	1,480 kg/m^3	2,150 kg/m^3
2.	Unit mass (loose)	1,380 kg/m^3	1,350 kg/m^3	1,980 kg/m^3
3.	Specific gravity (a) Saturated surface dry (b) Oven-dry	 2.61 2.68	 2.63 2.68	 2.58 2.60
4.	Percentage voids (compact)	41.2 percent	43.7 percent	17.3 percent
5.	Percentage voids (loose)	48.6 percent	48.7 percent	23.85 percent
6.	Percentage absorption	1.8 percent	1.18 percent	1.20 percent

3.2 Nature of Design variables

Water content (w), fine aggregate content (fa), coarse aggregate content (ca) and cement (c), all measured in kg/m^3 are taken as random design variables in the proposed reliability- based design optimization model. There is no random parameter and deterministic design variable. Also, in SORA method, it is required that all the random design variables follow normal distribution. Normal distribution of all the variables is ensured by drawing histograms and Q-Q plots for each zone of aggregates. Also, Kolmogorov-Smirnov test has been conducted to verify normality of variables.

3.3 Formulation of reliability- based optimization models for concrete mix parameters

The aim of the present study is to find the optimum mix proportions for minimum cost of concrete while keeping compressive strength for 28 days of concrete above a pre-specified level with a given reliability. Separate optimization models for each zone A, B, C of aggregates are solved. The objective function is to minimize the cost of concrete per m^3.

$$\begin{array}{ll} \text{Objective function} & \text{Minimize cost} \\ \text{Design variable} & DV = \{\mu_w, \mu_{fa}, \mu_{ca}, \mu_c\} \end{array} \quad \ldots(3)$$

Where cost = cost of concrete cubes per m^3 in rupees.

μ_w = Mean value of water content in Kg/ m^3

μ_{fa} = Mean value of fine aggregate content in Kg/ m^3

μ_{ca} = Mean value of coarse aggregate content in Kg/ m^3

μ_c = Mean value of cement content in Kg/ m^3

Equation (3) is subject to

- Reliability constraint on required compressive strength for 28 days of curing age.

$$\Pr(st28 \geq H) \geq R \quad \ldots\ldots(4)$$

Where $st28$ = compressive strength for 28 days in MPa

H = Target value for compressive strength in MPa

R = Target reliability level

- Boundary constraints

$$w_l \leq w \leq w_u \quad \ldots\ldots(5)$$

$$fa_l \leq fa \leq fa_u \quad \ldots\ldots(6)$$

$$ca_l \leq ca \leq ca_u \quad \ldots\ldots(7)$$

$$c_l \leq c \leq c_u \quad \ldots\ldots(8)$$

Where w_l, fa_l, ca_l, c_l are the lower bounds for water, fine aggregate, coarse aggregate, cement content; all measured in kg/m^3. W_u, fa_u, ca_u, c_u are the upper bounds for water, fine aggregate, coarse aggregate, cement content; all measured in kg/m^3

- Ratio constraint

$$(w/c)_l \leq w/c \leq (w/c)_u \quad \ldots\ldots(9)$$

Water-cement ratio (w/c) is taken as ratio constraint with $(w/c)_l$ and $(w/c)_u$ as lower and upper bounds.

The data given in Kumar [12] is analyzed to find upper and lower bounds for all the design variables and ratio (*w/c*) and are summarized in *Table* 5. The variances of all the four random variables are also provided in *Table* 5.

Table 5: Properties of variables

	w (kg/m^3)			fa(kg/m^3)			ca(kg/m^3)			c(kg/m^3)			w/c	
	w_l	w_u	σ_w^2	fa_l	fa_u	σ_{fa}^2	ca_l	ca_u	σ_{ca}^2	c_l	c_u	σ_c^2	$(w/c)_l$	$(w/c)_u$
Zone A	180	210	120.379	416.93	617.20	3528.386	1042.15	1198.40	2544.496	350	450	1488.971	0.42	0.55
Zone B	190	220	122.364	439.65	642.18	3393.957	1042.15	1252.05	3240.794	350	450	1406.25	0.42	0.55
Zone C	200	230	120.924	453.15	626.85	2469.862	798.48	945.60	1707.118	350	450	1030.22	0.42	0.55

3.4 Prediction of concrete parameters using regression analysis

Derivation of high- quality analytical equations that can be used to predict concrete parameters is very necessary to get good optimization results. For modeling 28 days compressive strength and cost of concrete, regression analysis is used. Water content (*w*), fine aggregate content (*fa*), coarse aggregate content (*ca*) and cement (*c*) measured in Kg/m^3 are taken as independent variables. Separate models are developed for each zone of aggregates A, B and C. A number of different linear and quadratic regression models have been tried. After a comparison of different models, the best models are given in *Equation* (10) – (15). The coefficient of determination R^2 for the proposed models are listed in *Table* 6.

For zone A of aggregates:

$$cost = 1.165 + 0.006w + 0.500fa + 0.555ca + 4.997c \quad \ldots\ldots(10)$$

$$st28 = -180.031915 - 1.248246w + 0.127393fa + 0.287055ca + 0.725960c + 0.002086w^2 - 0.0000998fa^2 - 0.000128ca^2 - 0.000640c^2 \quad \ldots\ldots(11)$$

For zone B of aggregates:

$$cost = 2.363 + 0.025w + 0.497fa + 0.557ca + 4.994c \quad \ldots\ldots(12)$$

$$st28 = -74.518738 + 0.362216w + 0.089401fa + 0.128976ca + 0.581553c + 0.001807w^2 - 0.000074fa^2 - 0.000062ca^2 - 0.000471c^2 \quad \ldots\ldots(13)$$

For zone c of aggregates:

$$cost = 1.176 - 0.090w + 0.518fa + 0.636ca + 5.016c \quad \ldots\ldots(14)$$

$$st28 = 62.929000 - 1.476889w + 0.035840fa - 0.038025ca + 0.655538c + 0.004654w^2 + 0.000184fa^2 + 0.000019ca^2 - 0.000758c^2 \quad \ldots\ldots(15)$$

Table 6: Coefficient of determination for proposed models

Equation No.	R^2
10	1.000
11	0.977
12	1.000
13	0.997
14	1.000
15	0.994

3.5 Optimization Results and Discussion

The reliability- based optimization models constructed for zone A, B and C of aggregates are solved by SORA method, which is explained in section 2.2. The optimization results for a wide range of target compressive strength and target reliability levels are obtained and are listed in *Tables* 7-9. In addition to optimum values of water, fine aggregate, coarse aggregate, cement content and water-cement ratio; values of fine aggregate- cement ratio and coarse aggregate- cement ratio have also been reported. Optimum concrete mix designs for nine levels i.e. 27, 30, 33, 36, 39, 42, 45, 48, 51 MPa of target compressive strength and reliability level from 0.90000 to 0.99865 are obtained. Following are the main observations from the optimization results:

- For zone A of aggregates, maximum target compressive strength for which more than 90% reliability can be assured is 45 MPa. For compressive strength greater than or equal to 48 MPa; no optimum solution is obtained for reliability ≥ 0.9.
- For zone B of aggregates, maximum target compressive strength for which more than 90% reliability can be assured is 48 MPa. For compressive strength greater than or equal to 51 MPa; no optimum solution is obtained for reliability ≥ 0.9.
- For zone C of aggregates, more than 90% reliability can be assured for each level of target compressive strength.

- For a particular value of target compressive strength, $^{w}/_{c}$ decreases as reliability level is increased for Zone A and B, but for zone C, *w/c* is 0.55 in almost each case.
- *w/c* is higher for zone C of aggregates rather than for zone A or Zone B.
- Maximum reliability level of 0.99865 cannot be achieved in each case. Maximum possible reliability level for which optimum solution can be obtained has been reported in *Tables* 7 – 9.
- Lowest cost of concrete for a given target compressive strength and target reliability level is obtained for zone C of aggregates.

Table 6: Optimization results for concrete mix with zone- A aggrgates

	R	*Cost*	*w*	*fa*	*ca*	*c*	*w/c*	*fa/c*	*ca/c*
$st28 \geq 27$	0.90000	2679.12	180.00	495.43	1042.15	370.38	0.486	1.338	2.814
	0.95000	2756.54	180.00	497.42	1042.15	385.67	0.467	1.290	2.702
	0.99000	2901.69	180.00	507.52	1042.15	413.71	0.435	1.227	2.519
	0.99865	3109.97	186.17	589.19	1077.65	443.27	0.420	1.329	2.431
$st28 \geq 30$	0.90000	2728.59	180.00	499.85	1042.15	379.83	0.474	1.316	2.744
	0.95000	2806.53	180.00	503.76	1042.15	395.04	0.456	1.275	2.638
	0.99000	2952.66	180.00	513.74	1042.15	423.29	0.425	1.214	2.462
	0.99700	3107.09	185.49	594.64	1082.10	441.63	0.420	1.346	2.450
$st28 \geq 33$	0.90000	2780.21	180.00	507.91	1042.15	389.36	0.462	1.304	2.677
	0.95000	2858.75	180.00	510.48	1042.15	404.82	0.445	1.261	2.574
	0.99000	3013.54	180.00	565.74	1057.40	428.57	0.420	1.320	2.467
	0.99500	3157.64	189.00	602.53	1090.86	450.00	0.420	1.339	2.424
$st28 \geq 36$	0.90000	2834.28	180.00	513.03	1042.15	399.66	0.450	1.284	2.608
	0.95000	2913.54	180.00	517.86	1042.15	415.04	0.434	1.248	2.511
	0.99000	3181.54	188.96	617.20	1120.71	450.00	0.420	1.372	2.490
$st28 \geq 39$	0.90000	2891.20	180.00	519.93	1042.15	410.36	0.439	1.267	2.540
	0.95000	2971.35	180.00	525.64	1042.15	425.83	0.423	1.234	2.447
	0.97000	3045.13	180.00	597.81	1085.42	428.57	0.420	1.395	2.533
	0.97900	3168.09	189.00	613.84	1099.49	450.00	0.420	1.364	2.443
$st28 \geq 42$	0.90000	2951.49	180.00	528.17	1042.15	421.61	0.427	1.253	2.472
	0.95000	3075.37	181.17	614.40	1099.84	431.36	0.420	1.424	2.550
	0.96000	3181.49	189.88	617.20	1120.61	450.00	0.422	1.372	2.490
$st28 \geq 45$	0.90000	3023.90	180.00	576.23	1066.61	428.57	0.420	1.345	2.489
	0.92400	3175.47	189.00	617.20	1109.77	450.00	0.420	1.372	2.466

Table 7: Optimization results for concrete mix with zone- B aggregates

	R	*Cost*	*w*	*fa*	*ca*	*c*	*w/c*	*fa/c*	*ca/c*
$st28 \geq 27$	0.90000	2696.23	190.00	439.65	1042.15	378.48	0.502	1.162	2.754
	0.95000	2769.81	190.00	439.65	1042.15	393.21	0.483	1.118	2.650
	0.99000	2908.55	190.00	444.30	1042.15	420.53	0.452	1.057	2.478
	0.99865	3046.57	190.00	456.08	1042.15	446.99	0.425	1.020	2.331
$st28 \geq 30$	0.90000	2753.57	190.00	441.96	1042.15	389.73	0.488	1.134	2.674
	0.95000	2827.61	190.00	445.45	1042.15	404.21	0.470	1.102	2.578
	0.99000	2967.21	190.00	453.91	1042.15	431.32	0.441	1.052	2.416
	0.99865	3162.71	190.00	527.53	1159.99	450.00	0.422	1.172	2.578
$st28 \geq 33$	0.90000	2813.40	190.00	448.21	1042.15	401.09	0.474	1.117	2.598
	0.95000	2887.93	190.00	452.71	1042.15	415.57	0.457	1.089	2.508
	0.99000	3028.57	190.00	461.33	1042.15	442.87	0.429	1.042	2.353
	0.99800	3213.22	190.00	525.98	1252.05	450.00	0.422	1.169	2.782
$st28 \geq 36$	0.90000	2876.03	190.00	454.83	1042.15	412.97	0.460	1.101	2.524
	0.95000	2951.14	190.00	460.44	1042.15	427.46	0.444	1.077	2.438
	0.99000	3102.38	190.00	538.21	1042.15	450.00	0.422	1.196	2.316
	0.99500	3210.62	190.00	520.75	1252.05	450.00	0.422	1.157	2.782
$st28 \geq 39$	0.90000	2941.87	190.00	463.92	1042.15	425.25	0.447	1.091	2.451
	0.95000	3017.72	190.00	468.52	1042.15	439.98	0.432	1.065	2.369
	0.99000	3246.56	190.00	593.08	1252.05	450.00	0.422	1.318	2.782
$st28 \geq 42$	0.90000	3011.53	190.00	472.41	1042.15	438.36	0.433	1.078	2.377
	0.95000	3091.53	190.00	516.36	1042.15	450.00	0.422	1.147	2.316
	0.97800	3250.72	190.00	601.44	1252.05	450.00	0.422	1.337	2.782
$st28 \geq 45$	0.90000	3087.31	190.00	507.88	1042.15	450.00	0.422	1.129	2.316
	0.95000	3219.90	190.00	539.42	1252.05	450.00	0.422	1.199	2.782

	0.95400	3250.83	190.00	601.66	1252.05	450.00	0.422	1.337	2.782
$st28 \geq 48$	0.90000	3213.09	190.00	525.73	1252.05	450.00	0.422	1.168	2.782
	0.91000	3250.83	190.00	601.66	1252.05	450.00	0.422	1.337	2.782

Table 8: Optimization results for concrete mix with zone- C aggregates

	R	*Cost*	*w*	*fa*	*ca*	*c*	*w/c*	*fa/c*	*ca/c*
$St28 \geq 27$	0.99865	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
$St28 \geq 30$	0.99000	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
	0.99865	2648.78	210.97	453.15	798.48	383.58	0.550	1.181	2.082
$St28 \geq 33$	0.99000	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
	0.99865	2693.43	215.91	453.15	798.48	392.56	0.550	1.154	2.034
$St28 \geq 36$	0.95000	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
	0.99000	2634.77	209.42	453.15	798.48	380.75	0.550	1.190	2.097
	0.99865	2738.81	220.94	453.15	798.48	401.71	0.550	1.128	1.988
$St28 \geq 39$	0.95000	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
	0.99000	2680.14	214.44	453.15	798.48	389.89	0.550	1.162	2.048
	0.99865	2784.98	226.05	453.15	798.48	411.00	0.550	1.103	1.943
$St28 \geq 42$	0.90000	2606.18	206.25	453.15	798.48	375.00	0.550	1.208	2.129
	0.95000	2624.74	208.31	453.15	798.48	378.74	0.550	1.196	2.108
	0.99000	2725.70	219.49	453.15	798.48	399.07	0.550	1.136	2.001
	0.99800	2812.01	229.04	453.15	798.48	416.44	0.550	1.088	1.917
$St28 \geq 45$	0.90000	2618.40	207.60	453.15	798.48	377.46	0.550	1.201	2.115
	0.95000	2670.49	213.37	453.15	798.48	387.95	0.550	1.168	2.058
	0.99000	2771.46	224.55	453.15	798.48	408.28	0.550	1.110	1.956
	0.99600	2838.08	230.00	453.15	798.48	421.66	0.545	1.075	1.894
$St28 \geq 48$	0.90000	2664.17	212.67	453.15	798.48	386.68	0.550	1.172	2.065
	0.95000	2715.88	218.40	453.15	798.48	397.09	0.550	1.141	2.011
	0.99000	2817.37	229.64	453.15	798.48	417.52	0.550	1.085	1.912
	0.99100	2857.18	230.00	453.15	798.48	425.47	0.541	1.065	1.877
$St28 \geq 51$	0.90000	2709.29	217.67	453.15	798.48	395.76	0.550	1.145	2.018
	0.95000	2760.89	223.38	453.15	798.48	406.15	0.550	1.116	1.966
	0.98100	2892.30	230.00	453.15	798.48	432.47	0.532	1.048	1.846

4. Conclusions

In this work an effort has been made to incorporate reliability into optimization process so that more realistic results can be obtained. Following conclusions have been drawn from the study:

1) Optimum cost of concrete mix increases as reliability level increases *i.e.* minimum cost has to be sacrificed to keep reliability above a pre specified level.
2) Concrete mix designs with Zone C of aggregates are most economical and more reliable than concrete mix designs with zone A or B of aggregates.

References

[1] N. Kuschel, R. Rackwitz, Two basic problems in reliability based structural optimization, Mathematical Methods of O`perational Research, 46 (1997) 309 – 333.

[2] J.O. Royset, A.D. Kiureghian, E. Polak, Reliability-based optimal structural design by decoupling approach, Reliability Engineering and System Safety, 73 (2001) 213-221.

[3] X. Du, W. Chen, Sequential optimization and reliability assessment method for efficient probabilistic design, ASME Journal of Mechanical Design, 126 (2004) 225 – 233.

[4] H. Aggarwal, Reliability based design optimization: formulations and methodologies, PhD thesis, University of Notre Dame, Indiana, 2004.

[5] T. Zou, S. Mahadevan, A direct decoupling approach for efficient reliability-based design optimization, Structral & Multidisciplinary Optimization, 31 (2006) 190 – 200.

[6] K. Sobolev, The development of new method for proportioning of high- performance concrete mixtures, Cement and Concrete Composites, 26 (2004) 901 – 907.

[7] C.H. Lim, Y.S. Yoon, J.H. Kim, Genetic algorithm in mix proportioning of high–performance concrete, Cement and Concrete Research, 34 (2004) 409 – 420.

[8] E. Özbay, A. Baykasoğlu, A. Öztas, H. Özbebek, An experimental comparison of optimum mix proportions of high strength concrete proposed by Taguchi method and genetic algorithm, In proceedings of 5th International Symposium on Intelligent Manufacturing Systems, 2006.

[9] M.A. Jayaram, M.C. Natraja, C.N. Ravikumar, Elitist genetic algorithm models: optimization of high-performance concrete mixes, Materials and Manufacturing Processes, 24 (2009) 225 – 229.

[10] B. Y. Lee, J.H. Kim, J.K. Kim, Optimum concrete mixture proportion based on a database considering regional characteristics, Journal of Computing in Civil Engineering, 23 (2009) 258 – 265.

[11] A. Baykasoğlu, A. Öztas, E. Özbay, Prediction and multi-objective optimization of high strength concrete

parameters via soft computing approaches, Expert Systems with Applications, 36 (2009) 6144 – 6155.

[12] M. Kumar, Reliability based design of structural elements, PhD thesis, Thapar University, Patiala, India, 2002.

[13] M.kumar, M.L. Gambhir, M.P. Kapoor, Reliability-based design of concrete mix, The Indian Concrete Journal, (2006), 9 - 19.

[14] X. Du, A. Sudjianto, W. Chen, An integrated framework for optimization under uncertainty using inverse reliability strategy, DETC2003/DAC-48706, 2003 ASME International Design Engineering Technical Conferences and the Computer and Information in Engineering Conference, Chicago, Illinous, 2003.