INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 28-10-2022

Accepted: 05-01-2023

Published: 03-02-2023

Citation: Jari Y, Abdulghafour A (2023) Investigation of Impact of Span Length and Variable Live Loading Conditions on Flat Slab Material Costs. Indian Journal of Science and Technology 16(4): 299-308. https://doi.org/10.17485/IJST/v16i4.2095

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Investigation of Impact of Span Length and Variable Live Loading Conditions on Flat Slab Material Costs

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Abstract

Objectives: This study investigates the optimization of reinforced concrete flat slabs and establishes a relationship between span, live load, and material costs. **Methods:** The study used the direct design method per Saudi Building Code limitations, iterative design, and pattern search methods to establish a mathematical model that prescribes the span-cost relationship. The study conducted variable live loading tastings and cost estimates on multiple flat slab panels with distinct dimensions. **Findings:** The results showed that slab material unit cost increases significantly with span while live load had little impact. Material costs included concrete, steel, and forms which compose 36%, 52%, and 12%, respectively of the total. Each increment in span by 1 meter raises slab material unit cost by 19% starting form 4 meters span as a baseline. Increasing live load by 1 kN/m^2 increase cost by roughly 2% for square panels and 1% for rectangular ones. However, results proved that using 1:1 panel dimension is more economical than panels with 2:1 ratio. **Novelty:** The study provided a mathematical model to estimate flat slab cost more accurately in preliminary estimations before the design phase.

Keywords: Material Costs; Flat Slab Cost; Live Load Impact on Cost; Span Impact on Cost; Slab Unit Cost; Cost Optimization

1 Introduction

1.1 Background

The flat slab structural system is commonly implemented in projects in Saudi Arabia due to the higher average labor-to-material-cost ratio in the country. This system provides multiple structural, architectural, and construction advantages. The absence of internal beams in flat slabs allows for quick and straightforward construction and simple formwork installation [1,2]; thus, higher productivity can be achieved even with mediocre labor skills that impact labor costs. This also provides minimum obstructions and complexity to placing mechanical and plumbing elements under the slab, including air conditioning ducts and pipes. From an architectural perspective, this system ensures significant flexibility and tolerance to architectural details and future changes regarding spaces or partition walls. However, flat slab main issue is that it requires more significant quantities of materials than other systems like hollow block (ribbed), or solid slabs (Beam-slab) systems, and in some cases post-tensioned slabs[3,4]. A flat slab system could be used to cover smaller spans as 4 meters to larger ones around 10 meters[5]. However, this wide coverage significantly impacts the relative building costs. Different slab spans have different costs per meter. Therefore, the questions arise, "what is the most optimum span range for flat slabs?". The answer to this question may differ from one location to another based on the proportional costs of different materials (concrete, steel, and formwork) and labor costs. However, in the context of Saudi Arabia and other Middle Eastern countries, the idea of cost optimization is still not sufficiently formed.

1.2 Related Studies

Research proved that Saudi Building Code (SBC-304) and American Concrete Institute (ACI-318) span-to-depth ratio requirements for one-way solid slab design always result in relatively conservative slab thickness values which leads to increased material costs[6]. Another concern revealed by parametric studies showed that disregarding the restraints from adjacent slabs during design may underestimate the load redistribution capability of the flat slab substructures which directly leads to more conservative designs[7]. Regarding the impact of line loading on flat slabs, studies indicates that the dimensions and loadings significantly affect the behavior of the structures[8]. Studies applied simulated annealing algorithm using yield lines and virtual work principle to optimize slab thickness and reinforcement design in the Italian construction market[9]. The recommended thicknesses for the middle and column strips are 130 mm and 140 mm, respectively, while optimal reinforcement ratios were 2% and 3.5% for the middle and column strips, respectively in accordance with British standards considering Nigerian market prices[10]. Another investigation in compliance with Egyptians code of practice (ECP-18) evaluated the impacts of varying column spacing and concrete grades on the optimal design cost. In terms of direct construction costs for low-rise RC residential buildings, the results recommended the use of concrete with a grade less than 40 MPa and column spacings up to 5 meters.[11]. Regarding optimization of pre-stressed slabs design, stresses are effectively countered when a greater proportion of tendons are concentrated rather than scattered. Concentrated tendons require less complications during construction, thus, less labor efforts and costs[12]. Another study suggested a simplified practical approach to evaluate the viability of fiber reinforced concrete column-supported flat slabs. The evaluations show an increase in fiber reinforced slabs direct costs which could be offset by a reduction in construction time and, as a result, time-dependent expenses[13]. From prospect of sustainability and operational costs, according to the findings, increasing the thickness of the concrete cover enhances structural durability, reduces costs and environmental consequences, thereby increasing predicted service life and contributing to more sustainable buildings[14]. Another study suggested the application of agile project management for projects in Saudi Arabia. The study proposed a procedure for selecting materials in all structural elements while considering cost and sustainability without sacrificing structural element function[15].

1.3 Aims and Novelty

The impact of span length on the unit cost of slabs has not been discussed comprehensively within the context of Saudi Arabia. The slab construction cost forms most of the reinforced concrete (RC) structural element's costs[2,16]. Since material construction costs constitute primary factors in the structural design of RC buildings[17,18], This research aimed to investigate the unit material cost and span length of RC flat slabs and establish a mathematical model to prescribe the relationship between span length and construction costs to optimize structural cost for flat slab projects in Saudi Arabia. The study aimed to achieve this by determining the most economical design of RC flat slabs. Therefore, the research included the impact of span length on the unit cost of the slab, the proportional cost ratio between individual slab materials, and the effect of multiple loading conditions on slabs.

2 Methodology

2.1 Procedure

The paper conducts research through five steps prescribed in Figure 1. First is the structural design of different slabs with various dimensions under multiple loading conditions. Then, estimating the required quantities and material costs provides the basis for the analysis. After that, the relationships between study variables are established by analyzing material cost data. Next, based on the data costs analysis, the study reviews and categorizes the results to prescribe a comprehensive discussion around the results and information prelude to the conclusion. Finally, we concluded the research and established the eventual recommendations.

Fig 1. Research Procedure

2.2 Direct Search Approach

Direct search approaches are usually utilized when solving issues when the objective function is not continuous and differentiable. In a stochastic or non-stochastic process, they primarily look at the objective function to find the optimum solution based on previous findings. It is frequently thought of as a general word for optimization algorithms that employ objective function values rather than gradients of objective functions. This definition of direct search fits many different methods used today. The study applied Pattern Search Methods (PSM), which fall under the category of direct search methods and iterative design approach to identify the optimum design characteristics and loading conditions to flat slab design [19].

2.3 Design Methods and Assumptions

The study applied the Direct Design Method following the limitations and requirements of the Saudi Building Code (SBC) to generate [20]. The direct design method is applicable for slabs with more than three continuous spans with rectangular panels having long/short span ration between 1:1 and 2:1. Successive span lengths in each direction must not have ratios of less than 2/3 and column offset not more than 10% of the maximum span length. Thus, the study considered typical slab of 4 duplicate panels in each direction. Only gravity loads are considered using direct method, therefore, the study didn't consider any lateral loads. The design incorporated loading conditions and material properties per the SBC requirements utilizing the ultimate state design [21] with characteristic concrete strength (fc) of 35 MPa while steel yield strength (fy) at 420 MPa. The structural cross-section design considered the minimum cover spacing for reinforcement as 25 mm. Slab design applied various loading conditions through multiple iterations for each panel case. Table 1 shows the used panel dimensions cases. The study selected panel combinations to preserve the 1:1 and 2:1 long/short span ratio in accordance with limitations of the direct design method. The span ranged from 3 to 14 meters in x-direction (l_x) and 3 to 7 meters in y-direction (l_y). The dead load is constant at 4 kN/m^2, excluding the slab's weight. Each slab case has been tested under variable live loads that are 4 kN/m^2, 5 kN/m2, 6 kN/m2, 7 kN/m2, and 8 kN/m2. With the mentioned variables, the study included a total of 150 design cases.

2.4 Iterative Procedure and Estimation

The paper used iterative design, variable live load testing, and quantities and costs estimation techniques to generate material quantitates data for cost analysis. The design process included the use of spreadsheet software to carry on the iterative procedures of design and estimations. The program algorithm we coded shown in Figure 2 conducts the design with minimal input variables. The input variables include the slab panel dimensions (l_x and l_y) and applied Dead Load (W_D) live load (W_L). The design constraints include concrete strength (f_c) and steel yield strength (f_y). Using the direct design method, the program calculates the slab thickness (h_s) and the required reinforcement area (A_s). The necessary reinforcement area (A_s) is used rather than intricate reinforcement patterns and detailed topology (number, diameter, longitudinal distribution of the steel bars, etc.) for simplification. Due to that, the number of required input variables was significantly reduced. The program then calculates the quantities of the required materials. The study principle is to determine the unit cost of the slab model for each case to achieve the most economical span. The developed software then calculates the total by applying Equation (1).

$$C = \sum C_c * Q_c + \sum C_s * Q_s + \sum C_f * Q_f. \tag{1}$$

Where: $C_c. C_s.$ *and* C_f are unit price of cubic meter of concrete, ton of steel, and equivalent plate of formwork, respectively and Q_c, Q_s. *and* Q_f are volume of concrete, weight of reinforcement steel, and area of formwork, respectively. The unit price of the materials was assumed as 200 SR/m^3 (53.33 \$/m^3) for concrete, 2500 SR/ton (666.67 $/ton) for reinforcement steel, and 100 SR/m^2 (26.67 \$/m^2) for formworks to be used six times. The prices have been selected to be close to the average unit price indexes published by the Saudi Contractors Authority (SCA) [22]. The study then, applied numerical procedure and fittings using MATLAB software to generate the mathematical model.

Table 1. Slab panels dimensions and loading Cases

		Panel Long Direction (lx) (m)												**Live Load (LL.) (kN/m2)**
		3	4	5	6	7	8	9	10	11	12	13	14	
Panel Short Direction (ly) (m)	3	S1	S2	S3	S4									
	4		S5	S6	S7	S8	S9							
	5			S10	S11	S12	S13	S14	S15					4
	6				S16	S17	S18	S19	S20	S21	S22			
	7					S23	S24	S25	S26	S27	S28	S29	S30	
	3	S31	S32	S33	S34									
	4		S35	S36	S37	S38	S39							
	5			S40	S41	S42	S43	S44	S45					5
	6				S46	S47	S48	S49	S50	S51	S52			
	7					S53	S54	S55	S56	S57	S58	S59	S60	
	3	S61	S62	S63	S64									
	4		S65	S66	S67	S68	S69							
	5			S70	S71	S72	S73	S74	S75					6
	6				S76	S77	S78	S79	S80	S81	S82			
	7					S83	S84	S85	S86	S87	S88	S89	S90	
	3	S91	S92	S93	S94									
	4		S95	S96	S97	S98	S99							
	5			S100	S101	S102	S103	S104	S105					7
	6				S106	S107	S108	S109	S110	S111	S112			
	7					S113	S114	S115	S116	S117	S118	S119	S120	
	3	S121	S122	S123	S124									
	4		S125	S126	S127	S128	S129							
	5			S130	S131	S132	S133	S134	S135					8
	6				S136	S137	S138	S139	S140	S141	S142			
	7					S143	S144	S145	S146	S147	S148	S149	S150	

3 Results and Discussion

3.1 Slab Unit Cost Analysis

This section prescribes the computing of the materials required quantities and minimum steel reinforcement after the determination of slab design characteristics. The following Tables show the quantities and cost data output from the spreadsheet for all slabs included in the study. Each table considers the slab design under certain live load conditions. The slabs have been divided into five categories based on live load. Each category is further divided into groups based on the short panel dimension. For instance, slab S25 falls in group 5 in category 1 (C1G5). Table 2 shows the overall unit cost summary for each slab.

The analysis results for slabs unit cost in category one under a live load of 4 kN/m^2 ranges from 81 SR ($21.6) to 238 SR ($63.5), around three times increment. Slab S1 had the lowest cost, while S30 had the peak. Slabs S1, S5, S10, S16, and S23 had the lowest unit cost between slabs for each group within the same category, while S4, S9, S15, S22, and S30 costs were the greatest. The results show a proportional increase in unit cost with span length. Regarding the proportionate materials costs, steel reinforcement percentages from the total appear to increase with increment of span length while Formworks' share of cost decreases. Steel cost percentage varied from 42% to 56%, and formworks decreased from 21% to 7%, averaging 50%, and 13% for steel and forms, respectively. The span length seems to have little to no impact on the concrete share of costs, with a slight variance from 35% to 38% and an average of 36%. This could be detrimental for projects in regions with low availability of wood or steel and their respective costs. However, this is subject to the study of steel and wood base costs in any given region. Results related to category two slabs shows similarity to category one. Unit costs analysis was almost identical to the previous findings that S31, S35, S40, S46, and S53 had the lowest costs, while S34, S39, S45, S52, and S60 had the lowest unit costs. The unit costs varied from 81 SR ($21.6) to 242 SR ($64.5). The materials costs percentages for category two were also similar, with an average of 36% for concrete, 51% for steel, and 13% for forms. The results of category three follow a similar pattern to those

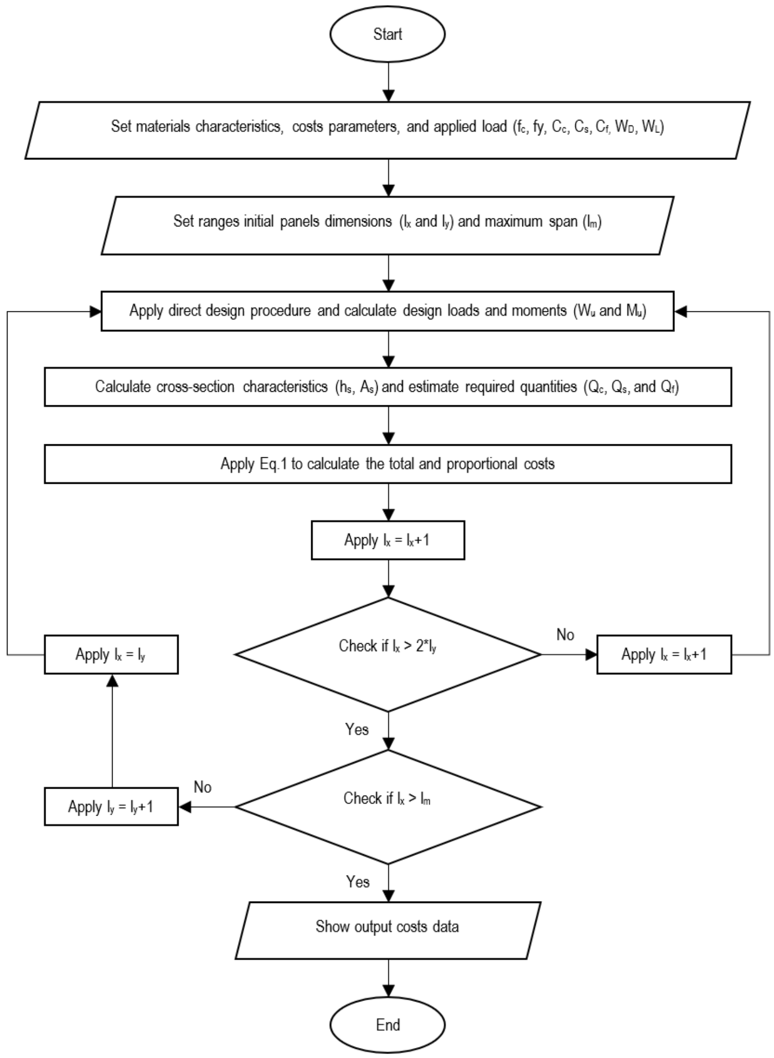

Fig 2. Iterative Design-Estimation Software Algorithm

of categories one and two. The shortest slab in each group had the lowest cost, while the longest had the greatest value. The material percentage costs also follow a similar form. This would continue with the results of categories four and five.

3.2 Cost vs Span Model

The analysis shows that the increase in slab length significantly multiplies the material costs, a pattern corresponds with findings in similar studies [11] as shown in Figure 3. The figure illustrates the impact of increasing span length over the structural element unit cost. The analysis showed that increasing the span length from 6 meters to 12 meters increases the unit cost by approximately 100%. In this case, from 105 S.R./m^2 to 210 S.R./m^2, with of roughly 15 SR/m^2. The increase in the unit cost seems to follow a consistent approach since the output almost represents a straight line, which exhibits a steady increase except for a jump between 5 meters and 6 meters. However, increasing span from 4 to 8 meters increase slab unit cost by 66%, which shows significant increase relative to other studies [16] that indicates only 37% increase for the same interval. This contrast could be the product of introduction of other factors in their study including multiple stories, other elements costs, or labor cost while this study scope focused only on the unit cost of material of flat slabs. This reduces the detailing efforts and labor skills required to maintain productivity. It is safe to assume that every 1-meter increase in length results in a 19% and roughly 16.1 SR/m^2 increment in material cost/m^2 of the slab starting from 4 meters to 14 meters, with a 192% increase. The increment in slab panel width shows

Table 2. Slabs unit cost summary

Live Load (LL.) (K.N./m2)			Panel Long Direction (lx) (m)												Average Unit Cost for Load (SR.)
			3	4	5	6	7	8	9	10	11	12	13	14	
4	Panel Short Direction (ly) (m)	3	81	82	88	107									140
		4		83	90	108	119	138							
		5			92	109	120	139	151	170					
		6				112	123	141	153	172	184	204			
		7					126	143	155	173	186	205	218	238	
5		3	81	82	89	108									142
		4		84	91	109	121	139							
		5			94	111	122	141	153	172					
		6				113	125	143	155	174	187	206			
		7					129	145	157	176	189	208	221	242	
6		3	81	83	91	109									144
		4		85	93	110	122	141							
		5			96	112	124	143	155	175					
		6				116	127	145	157	176	189	209			
		7					132	148	160	179	192	211	225	245	
7		3	81	84	92	110									146
		4		86	94	112	124	143							
		5			98	114	126	145	145	177					
		6				118	129	147	160	179	192	212			
		7					135	150	163	181	195	214	228	248	
8		3	82	84	93	111									149
		4		87	96	113	126	145							
		5			100	116	128	146	160	179					
		6				120	132	149	162	181	195	214			
		7					138	153	166	184	198	217	231	251	
Average Unit Cost for Span (SR.)			81	84	93	112	126	144	157	176	191	210	225	245	144

similar results. This behavior clarifies the advantage of maintaining square slab panels and similar dimensions. Therefore, it is advisable to maintain uniform panel dimensions ratio of 1:1 during design as much as possible to cover large areas and provide a simple and economical design. Similar panel dimensions also provide multiple advantages in construction since most aspects would be similar in both directions, thus reducing the detailing efforts and labor skills required to maintain productivity. The study developed a mathematical model to prescribe the relationship between the average unit cost for all values corresponding to the same span length in each group within each category. Figure 4 indicates the relationship between average unit cost affected by span length. Applying numerical procedure and fitting techniques, we established that the slab unit cost has a proportional linear relationship to span length. The relationship could be prescribed with the function illustrated by Equation 2. Figure 5 shows the plotted curve of equation.2.

$$Cu = y = f(x) = 15.5x + 20 \quad (2)$$

Where Cu is the unit cost per one unit area of RC slab and x is span length.

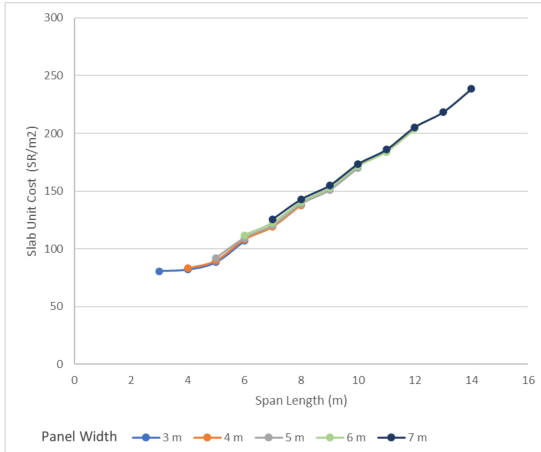

Fig 3. Slab Unit Cost – SpanLength

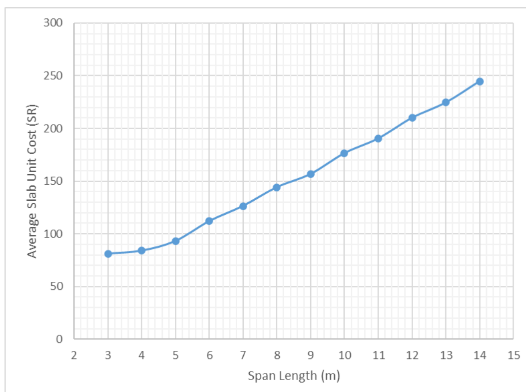

Fig 4. Average Unit Cost to Span Length

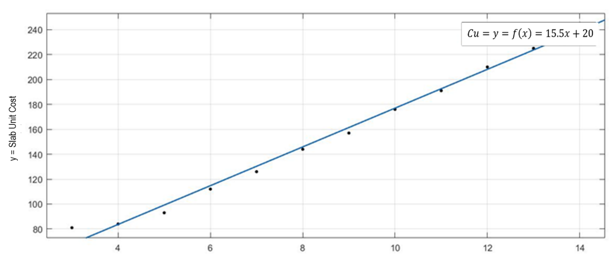

Fig 5. Slab Unit Cost – Span Length (Plot Equation 2)

3.3 Live loading Impact on Cost

Regarding the variable live load impact on slab cost, the study showed that live load increment increases slab material unit cost/m^2 slightly. Figure 6 shows the effect of increasing the live load on the structure material unit cost per meter area for a slab panel of 7 meters in width and variable length. As shown in Table 3, the unit cost increase in a linear pattern for each 1 kN/m^2 increase in live load. However, panel sizes with a ratio of 1:1 dimension showed an increment rate of 2 % except for 3*3m, while for panels with a 2:1 ratio, the increment rate is around 1%. Thus, panels with 2:1 ratio are less affected by live load increment than 1:1 ratio panel. This pattern may provide insights for farther study to identify the optimal design with combination live load and span impact, simultaneously.

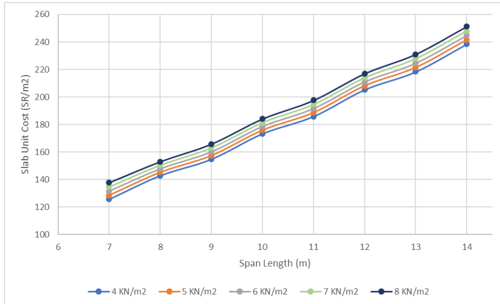

Fig 6. Unit Cost under Multi Live Load cases

Table 3. Impact of Increased Live Load on Slab Unit Cost

Dimensions		Live Load (kN/m^2)					Increment% per 1 kN/m2
Long	Short	4	5	6	7	8	
3	3	81	81	81	81	82	0
4	4	83	84	85	86	87	1
5	5	92	94	96	98	100	2
6	6	112	113	116	118	120	2
7	7	126	129	132	135	138	2
6	3	107	108	109	110	111	1
8	4	138	139	141	143	145	1
10	5	170	172	175	177	179	1
12	6	204	206	209	212	214	1
14	7	238	242	245	248	251	1

3.4 Material Cost Breakdown

The reinforced concrete material's proportional costs vary for each studied case. In addition, the analysis showed that the proportionate cost of each of the three components is affected by the increment in span length. Figure 7 shows each item's Material cost ratio and how it is affected by the increase in span length. The concrete cost composes around 35% at seven meters span length, the reinforcement steel 52%, and the form 13%. When increasing the span to 14 m, the cost of concrete composes 36%, the reinforcement steel cost percentage increase to 57%, and formworks decrease to 7%. Finally, at a 3m span, the concrete cost composes around 37%, the reinforcement steel is 42%, and the formwork 21%. This behavior allows us to determine that an increment in slab span length increases the proportional cost/m^2 of reinforcement steel and decreases the proportional cost of forms per area by 14%. In comparison, the concrete proportional costs remain relatively constant at 35-37%. In the end, as shown in Figure 8, concrete composes 36%, reinforcement 52%, and form work 12% of the total cost of reinforced concrete slabs. Other studies revealed different proportional material costs which indicated that 22% for concrete, 35% for steel, and 13% for forms and labor [2]. Another study showed that concrete, steel, and forms compose 27.8%, 48.8%, and 23.4%, respectively [23]. It should be noted that this variation may be attributed to variation of local prices between different regions and inclusion of labor cost.

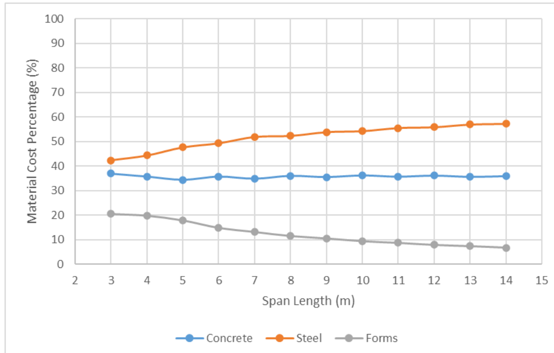

Fig 7. Reinforced concrete material cost breakdown

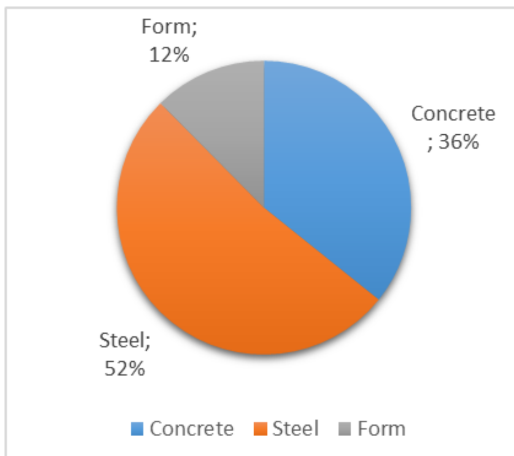

Fig 8. Average overall material costs percentage

4 Conclusion

The study investigated the impact of span length and live load increase on slab material cost. The study focused primarily on flat slab structures for projects implemented in Saudi Arabia. The study confirmed that increasing slab span considerably increases unit cost while the increase in live load minimally affects unit cost. Using the numerical procedure, we developed the mathematical model prescribed by Equation 2 to facilitate a relationship between span length and unit cost. The model can be implemented to allow a more accurate estimate of flat slab costs using span length only. This could be beneficial for early project estimates, especially in preliminary estimations before the completion of the design phase. The model would also enhance the application of value engineering principles through more accurate estimations and consideration of variable span designs. However, the model did not factor in the costs for other slab structural systems. Further study would improve the model or generate a novel one to consider solid slabs, ribbed slabs, or prestressed elements. In addition, further research would include prices for specific periods or any local region indexes to introduce time value and location local prices that affect the model.

The study results showed that a panel with a 1:1 length-to-width ratio seems more economical than panels with 2:1 dimension ratio; therefore, the authors recommend maintaining square dimensions as much as possible. Regarding live load testing, analysis revealed that panels with 2:1 ratio are less affected by live load increment than 1:1 ratio panel. This could be the subject of further study to confirm and conclude the theory. Since the study generally covered flat slab structures without considering building function, the authors recommend studying the optimal design with combination of live load and span impact simultaneously for specific building functions covering residential, commercial, health, educational, or administrative buildings.

The RC material costs are categorized into concrete, reinforcement steel, and formwork. Generally, the concrete cost would compose 36% of the total material cost. The reinforcement steel consumes the most significant portion of the RC material budget, representing 52% of the total costs. The formwork is a minor contributor, with only 12% of the total. Therefore, further studies regarding cost optimization should be more focused on reinforcement steel. However, our study only covered materials base costs and did not consider the labor, equipment, or project indirect costs, which would form the bases for further research. The effect of columns and the impact of other structural elements can also be explored.

Acknowledgment

The authors would like to thank the College of Engineering and Islamic Architecture and Deanship of Scientific Research at Umm Al-Qura University for supporting this work.

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