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POTENTIAL LEED CONSIDERATIONS FOR POST-TENSIONED CONCRETE STRUCTURES

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The aim of this paper is to study the potential future considerations for LEED (Leadership in Energy and Environmental Design), which is utilized by engineers, architects and construction managers. The study focuses on the New Construction category related to post-tensioned concrete design, construction and performance, and investigates whether LEED should consider adding a section, or extending its existing Innovation in Design section, to include more emphasis on structural frame details. Based on the study, it is shown that many of the advantages of post-tensioned construction mentioned earlier are environmentally beneficial qualities that are not categorized or specifically rewarded during the LEED certification process and thus post-tensioned structures deserve more LEED attention.

KEYWORDS

post-tensioned concrete; LEED; environmental saving; space efficiency.

INTRODUCTION

The aim of this paper is to study the potential LEED[1] (Leadership in Energy and Environmental Design) considerations for post-tensioned (PT) concrete structures. The LEED program was developed by the United States Green Building Code (USGBC) to act as a green building certification program. It has emerged as a nationally recognized benchmark for design—a way to certify that a building was specifically designed for better environmental and health performance.[2] LEED resources are used by everyone from engineers to architects to construction managers—basically anyone in the construction industry looking to develop sustainable projects—and potentially take advantage of tax incentives that are being created to reward certified projects. There are different rating systems depending on what type of construction is being evaluated: Homes, Neighborhood Development, Commercial Interiors, Building Operations and Maintenance, Interior Design and Construction, and Building Design and Construction. A project is evaluated in eight different areas: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. Depending on the points accumulated throughout these categories, there are different levels of certification: Certified, Silver, Gold, and Platinum, with the latter being the highest.[3] Green building and energy efficiency are international concerns, and there are other certification programs available worldwide (such as Green Globes, popular in Europe and Canada), but LEED is the most popular in the United States and will be the standard used for this paper. Additionally, this paper focuses on the New Construction category, following LEED-NC-v4, as we look at all eight LEED categories related to PT concrete design, construction, and performance. Ultimately, the purpose of this paper is to investigate whether LEED should consider adding a section, or extending its existing Innovation section, to include more emphasis on structural frame details.

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GREEN ASPECTS OF CONCRETE STRUCTURES

Concrete has been well established as a sustainable building material.[4] The many components of concrete each provide their own potential for sustainability considerations.[5] Perhaps the most encouraging feature, beyond all the environmentally friendly angles of concrete to be discussed, is that the finished appearance is desirable and customizable, increasing the likelihood that clients and builders will continue to use this material.

When considering the energy efficiency of the finished concrete product, the term "thermal mass" is always mentioned. This means a mass can absorb, store, and later release heat energy. A concrete structure can absorb the heat of summer to help regulate indoor temperatures, saving energy not only in the operating costs of heating, ventilation, and air-conditiioning (HVAC) systems but also reducing the overall size of the system needed and reducing overall project costs. Additionally, leaving light-colored concrete surfaces in an interior space reduces lighting needs, saving project costs on fixtures and operating costs for the building life cycle.

Fig. 1—Case study building. (2201 Westlake, Seattle, WA; Designed by Cary Kopczynski & Company)

Fig. 2—Case study building under construction.

To fully evaluate a material's sustainability, one must also look at the manufacturing process. Acquiring aggregate has ecological impacts, as does any process that extracts from earth, but quarries can be reclaimed as parks and recreational facilities. However, manufacturing is where cement falls short in environmental health. The most-discussed issue is CO_2 emissions. It's estimated that for every (1.1 ton) tonne of cement produced, (0.99 tons) 0.9 tonnes of CO_2 are emitted. This accounts for 7% of the world's CO_2 emissions annually.[6] There are also recent research programs dedicated to testing alternate fuels for the cement-production process—specifically, waste products such as spare tires and used motor oil. While these alternate fuels won't solve the emissions problems, burning them in kilns for cement production will prevent them from being dumped into landfills. A final consideration in the manufacturing process is the solid waste, cement kiln dust (CKD). Fortunately, a full 75% of CKD can be recycled for uses such as soil stabilization.

The mixture design is another area where general efficiency can be achieved. Limiting the amount of cement in the mixture by adding only the necessary amount needed to develop the required strength, using other binders in addition to portland cement, and reducing water content can form a strong, durable mixture that is both cost-efficient and environmentally friendly. Considering the aggregate gradation can also reduce the amount of cement needed in a mixture design, because a well-graded aggregate can provide interlocking and reduce the requirements of the bonding agent. With regard to other binding agents, termed supplementary cementitious materials (SCMs), there are several options available, such as fly ash, slag cement, silica fume, or rice husk ash, which are all by-products themselves. A noteworthy nonstructural sustainable use of concrete is pervious concrete pavements. This specific application of concrete has a 15 to 25% void structure which allows water to seep through, enabling groundwater recharge and reducing surface runoff (and associated pollutants). The special mixture design, which has little to no sand to achieve the voids in the finished product, does have reduced strength properties, but is useful for many applications.

Concrete differs from other construction materials, such as steel, in that it requires formwork for cast-in-place construction. This formwork is an added cost and also has environmental impacts because it is a potential source of construction waste. Fortunately, there are options such as steel or aluminum forms that can be reused; permanent formwork or precast systems are available to eliminate this concern all together.

Another construction need for concrete is water. There are some current practices that keep water use to a minimum, such as the reuse of ready mix wastewater. The Environmental Protection Agency (EPA) stipulates that this wastewater can't be disposed of into the ground or into storm sewers, so recycling is a logical choice.

The potential to recycle materials is always considered when doing a life-cycle analysis for a project. There are several ways to reuse concrete, the most common of which is to crush it and use it for aggregate in a new mixture. There are concerns with this method, such as the higher rate of absorption of particles relative to natural aggregate; difficulty in controlling the particle size distribution during the crushing process, which could result in too many fines; and the chlorine content, which is always a concern in reinforced concrete (RC) structures because of its degrading effect on reinforcing steel. However, in the past few years, there has been research on new mixture designs taking these factors into consideration.

Finally, as with any construction method, the use of local materials results in environmental and cost savings. Not having to ship aggregate and steel from afar to a construction site reduces energy and emissions. Overall, concrete is an impressive building material with the potential for aggregate, SCMs, water, manufacturing, and construction practices to all use environmentally sustainable methods.

CONCRETE STRUCTURES AND LEED

As was previously stated, LEED-New Construction evaluates projects in eight areas: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. Many of the LEED credits are geared more toward electrical and mechanical systems, but there are some dedicated to material selection, which are the focus of this paper. The idea that concrete is a sustainable building material from a life-cycle perspective surfaces in the following paragraphs, specifically related to using recycled materials from existing structures or recycled content in general.

Barth[6] listed many examples of LEED categories where concrete structures can potentially pick up points. The probable points and the category in which they appear are summarized in Table 1. Each is discussed individually, with the final credit regarding innovation being discussed specifically in regard to PT structures.

It should be mentioned that before any of these credits can be added toward LEED certification, the project must first meet the prerequisites for each category. Also, these suggestions are by no means the minimum credits that should be explored in each category; they are just the topics most related to concrete and PT construction.

The properties of pervious concrete pavements were briefly discussed earlier, and their benefits in reducing stormwater runoff, and therefore groundwater recharge, place them in the Sustainable Sites (SS) Credit: Rainwater Management. While pervious concrete would not be considered for use as a structural material, it is still a simple option for a project that is going to use concrete pavements.

Another nonstructural consideration related to concrete surfaces is the impact on the heat island effect. The heat island effect is a trend where urban temperatures are higher than rural temperatures, so LEED rewards construction that implements surfaces that are shaded

Table 1—Concrete-related LEED categories

Category	Topic	Potential points
SS Credit: Rainwater Management	Pervious concrete pavements	2-3
SS Credit: Heat Island Reduction	Concrete surfaces as heat-reducing islands	1-2
EA Prereq: Minimum Energy Performance	Concrete thermal mass effects	Required
MR Prereq: Construction and Demolition Waste Management Planning	Existing concrete buildings on site	Required
MR Credit: Building Life-Cycle Impact Reduction	Use of recycled concrete for construction fill	2-5
MR Credit: Construction and Demolition Waste Management	Recycled reinforcing steel	1-2
MR Credit: Building Product Disclosure and Optimization-Material Ingredients	Use of fly ash or slag	2-5
EQ Credit: Low-Emitting Materials	Use of low-VOCs for form sealants and coatings	1-3
EQ Credit: Daylight	Daylit floor area	1-3
IN Credit: Innovation	Innovative design using PT	1-5

or use paving materials with a 3-year aged Solar Reflectance (SR) value of at least 0.28 for Sustainable Sites Credit: Heat Island Reduction. This credit applies to both roof and non-roof surfaces. For roof construction, this credit is awarded for materials with a 3-year aged Solar Reflectance Index (SRI) value of at least 64 or 32 depending on the roof slope (low-sloped or steep-sloped, respectively).

The thermal mass benefits of concrete were introduced earlier, and they enter into LEED considerations in the Energy and Atmosphere (EA) Prerequisite: Minimum Energy Performance or potentially the EA Credit: Optimize Energy Performance. The prerequisite assures that a project meets Energy Standards and the thermal mass properties of concrete help to ensure that "components have enough heat-storage capacity to moderate daily temperature swings."[7] The use of concrete may also help gain LEED points in the first credit in the EA category, which can be worth 1 to 18 points depending on energy optimization. The percentage of energy cost savings is determined by the use of software that compares the building's performance to a standard or baseline building. The greater the energy savings, the more points awarded. Studies have shown that using concrete walls can add 1 to 3 points in this category, depending on climate and building type and orientation.[7]

Using old tires to power cement plants is an example of using recycled material instead of raw energy sources and also keeps tires out of landfills. This would be a consideration in *Materials and Resources (MR) Credit: Building Product Disclosure and Optimization-Environmental Product Declarations,* which encourages product selection based on improved environmental life-cycle impacts. The use of recycled concrete as construction fill could apply to *MR Credit: Building Life-Cycle Impact Reduction*, or if it was recycled concrete from an existing structure it could be applied toward *MR Prerequisite: Construction and Demolition Waste Management Planning*.

Returning to the subject of recycled content used, adding fly ash to the mixture design will also contribute to *MR Credit: Building Product Disclosure and Optimization-Environmental Product Declarations* because SCMs qualify as "pre-consumer and recycled material." Fly ash could also be considered in the *MR Credit: Building Product Disclosure and Optimization-Material Ingredients* because it improves the life-cycle impacts of concrete products. A high-volume fly ash (HVFA) mixture reduces the amount of cement used and therefore the CO_2 emissions associated with cement production, so fly ash could also be pitched as an *Innovation* point.

If there are existing concrete buildings on site, and any components can be saved and reused, LEED points can be gained from *MR Credit: Construction and Demolition Waste Management*. It is more difficult to reuse concrete components from an existing structure because integrating them into new construction is difficult. However, post-tensioning is one of the most popular methods for rehabilitating existing buildings. It is also common for components to be crushed and recycled as fill and the reinforcement saved. Reinforcement can be reused, in which case these components would contribute to the Construction and Demolition Waste Management credit as well.

Most concrete construction requires formwork whether it's permanent, temporary, steel, or wood (an exception would be concrete-filled steel tube construction where the steel tube itself serves as the containment method). Regardless, the sealants used on formwork can be specified as low-emission or reduced volatile organic compound (VOC) contents. VOCs are emitted by a variety of chemicals and building materials and may cause health problems,[8] so they are a concern both during the construction process and throughout the building's use. Environmentally friendly sealants are recognized in *Indoor Environmental Quality (EQ) Credit: Low-Emitting Materials.* While the main focus of this discussion is new construction, it should be mentioned that when rehabilitating existing structural components, post-tensioning is a superior option to fiber-reinforced polymers in the environmental quality category because of the epoxy and resins used in the latter strengthening method.

As previously discussed, post-tensioned design opens possibilities for irregular column layouts and unique interior spacing, presenting the opportunity to earn *EQ Credit*: *Daylight*. This credit has options requiring that there be daylit floor area for 75% of the regularly occupied areas minimum to earn points, which can be a challenge depending on the building use.

POST-TENSIONED CONCRETE ADVANTAGES

Post-tensioning has many advantages over plain and regular reinforced concrete. These advantages provide opportunities to gain LEED points; this paper discusses these advantages and then explains where and why they contribute to a LEED-certified project.

PT concrete structures have many advantages: reduced beam and slab depths, longer spans,[9] and flat-plate construction.[10] Improved serviceability, reduced foundation size and benefits in unstable soil, a fast construction cycle, and architectural advantages should also be discussed.

Reduced beam and slab depths mean lighter sections (typically a 20 to 30% reduction) and cost savings. Along with this comes reduced floor-to-floor height, and in a 200 ft (61 m) tall building, this can mean a few extra stories. Space efficiency is increased with longer spans between columns and no drops around beam-column connections. The greater interior free space is a huge plus for building owners because of the added flexibility in use.

Reduced foundation sizes mean less excavation (which translates into cheaper, quicker construction and less environmental impact). PT concrete foundations are increasing in popularity for areas with unstable soils because the stiffer slabs better resist soil movements.[10] Seismic demands are also reduced in PT structures.

The key to gaining the improved serviceability that allows the shallower sections and all their accompanying benefits is the practice of having the tendons drape in typically parabolic profile in the beam, thus balancing a large portion of the self weight.

In addition to all the cost savings from material reduction, there are other financial incentives regarding PT construction. Over the life cycle of a building, there are substantial savings in annual maintenance costs.

Architecturally, PT concrete structures provide unique possibilities. The aforementioned longer spans between columns mean more flexibility for interior space use. Also, the increased performance of PT members permits long cantilever options for both slabs and beams. Furthermore, there is the possibility of irregular column layouts.

It is only fair that some disadvantages of PT concrete construction be discussed as well. The construction process is more sophisticated, and specialized detailing of members is required. Increased slab shortening has been observed. The frequency of cracking is a concern, especially if the concrete surface is going to be a decorative component of the final product, such as with stained concrete flooring. Stage stressing is being used to successfully address this problem by applying a partial prestressing force soon after concrete placement and adding the full prestressing force when the concrete reaches the necessary strength, as opposed to applying the entire load at one time. As PT construction was gaining popularity, there was some worry about water infiltrating the end caps, causing tendon corrosion. Fully encapsulated tendons have been developed to tackle the latter. Despite the few disadvantages, PT concrete construction is increasing in popularity, and for good reason, as discussed in this paper.

POST-TENSIONED CONCRETE AND LEED

The idea that innovative design using PT concrete can earn only one LEED point in the Innovation (IN) category is something that needs to be addressed. There are only four innovation points available, and projects often implement many ideas that could be applicable toward these points (durability, concrete walls and ceilings with no coating, or the use of fly ash are three examples applicable to any concrete structure[7]). It has been shown that PT structures offer many advantages over traditional concrete construction, and other structures in general, and deserve LEED attention beyond a single innovation point.

For example, many of the advantages of PT construction mentioned earlier are environmentally beneficial qualities that are not categorized or specifically rewarded during the LEED certification process, such as material savings, energy savings, reduced construction schedule, reduced excavation, and an overall efficient structural system. To get a better idea of how these things are incorporated into a project, this paper moves on to study an existing PT concrete structure, 2201 Westlake, Seattle, WA (Fig. 1 and 2).

CASE STUDY AND DISCUSSION

2201 Westlake (Fig. 1 and 2) was featured in Maingot's[4] August 2009 article in the *PTI JOURNAL* as an example of green building. Maingot's correspondence and information from Sellen Construction, the general contractor on the project, are the sources for the information presented in this case study.

The 2201 Westlake project was seeking Silver LEED certification, so it incorporated many green features. Some were discussed previously, such as using recycled reinforcing steel (an estimated 97% of all steel is recycled) and specifying non-VOC paints, sealants, and adhesives. Others include general building features such as energy-efficient appliances.[4] The increase in spans between columns adds a user comfort advantage and also contributes to the LEED Indoor Environmental Quality credit for Daylight and Views (EQ Credit 8.2), as discussed previously. The impact of open spaces on HVAC systems should also be researched and if open spaces are beneficial to the system performance, this could be another LEED consideration for PT concrete structures.

The amount of materials that went into this project is astounding: 36,866 yd^3 (28,166 m^3) of structural concrete 4337 tons (3934 tonnes) of reinforcing steel and 335 tons (304 tonnes) of post-tensioning tendons. Material savings

Fig. 3—Unbonded post-tensioned wide beam-slab-column connection. (Photo: Cary Kopczynski & Company)

Fig. 4—Unbonded post-tensioned wall-slab connection. (Photo: Cary Kopczynski & Company)

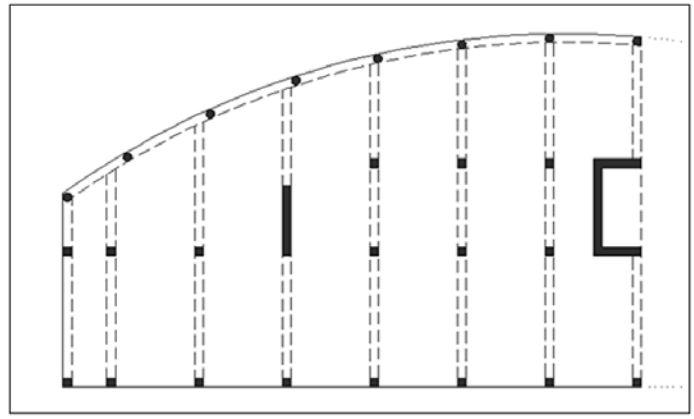

Fig. 5—PT framing plan.

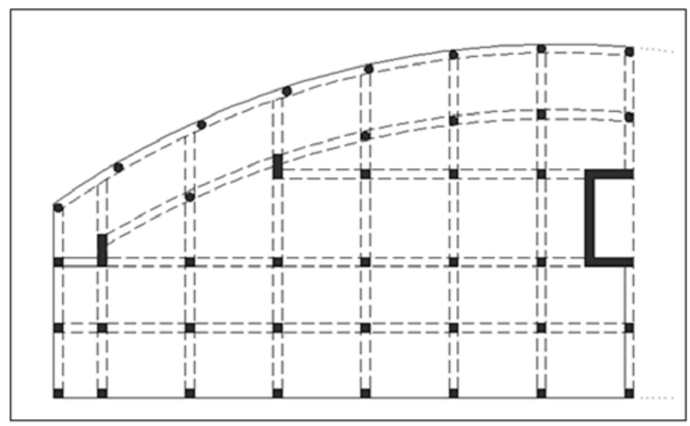

Fig. 6—RC framing plan.

come from the use of post-tensioning directly, because it can be estimated that post-tensioning tendons replace 2.5 to 3 lb. (1.1 to 1.4 kg) of reinforcing steel and the reduction in total concrete used can be estimated from the reduced beam and slab depths (Fig. 3 and 4) and column requirements. From a reinforcement perspective, this means that, conservatively, 503 tons (456 tonnes) of reinforcing bar were saved compared to a regular RC structure. Keep in mind that a savings in material means not only a reduction in manufacturing and raw material needs but also a considerable savings in transportation needs and associated emissions.

The reduction in beam depths and column frequency has been discussed, and an estimation of the actual materials savings in this structure compared to a regular RC structure support the notion that post-tensioning saves materials. A large direct materials savings comes from the reduction in slab thickness. The PT slab is 8 in. (203 mm) thick, while a comparable RC slab would be around 10 to 11 in. (254 to 279 mm) thick. Using a 2 in. (51 mm) differential thickness over a building area of 450,000 ft^2 (41,805 m^2) means 75,000 ft^3 (57,300 m^3) in total volume reduction. The reduction in beam depth does not present as large of a material savings because in PT construction the use of wide beams still requires a large volume of concrete. Details on the calculations used to make these conclusions are shown at the end of this paper.

One advantage of increased span lengths is the reduced number of columns a structure will require. The exact material savings are difficult to exactly calculate because built-up walls are often used to support loads, not just individual columns. Calculations show PT construction could use half the number of columns as a comparable

RC structure. With the difference in typical column sizes, the material savings could be estimated at 14,000 ft^3 (10,700 m^3) total.

In summary, using PT concrete structural framing on the 2201 Westlake building saved an estimated 503 tons of reinforcing steel and possibly close to 90,000 ft^3 (68,760 m^3) in total volume reduction, which would mostly be structural concrete.

Figures 5 and 6 were drafted to provide a visual comparison between the column and beam requirements of a PT floor plan compared to a traditional RC floor plan. While not based on actual dimensions or design load calculations, comparing the two figures easily demonstrates where the material savings comes from. Also, these graphics only depict the materials savings for the horizontal members, but there is also the slab thickness and the column height reduction discussed previously.

It is well known that construction sites disturb the habitats and surrounding environment. So it comes as no surprise that a reduced construction schedule as a result of post-tensioning is beneficial. As soon as the concrete has met the required strength the tendons can be stressed, which releases the load from the formwork.

CONCLUSIONS

This paper suggests the potential future considerations for LEED related to PT concrete structures, and investigates whether LEED should consider adding a section, or extending its existing Innovation section, to include more emphasis on structural frame details. Based on the study, it has been revealed that the fact that innovative design using PT concrete can earn only one LEED point in the Innovation (IN) category is something that should be urgently addressed. As such, PT structures offer many advantages over traditional concrete construction, and other structures in general, and deserve LEED attention beyond a single innovation point.

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CASE STUDY EXAMPLE

Reinforcement

A total of 2.5 lb (1.1 kg) of reinforcing bars are required to replace each pound of post-tensioning tendons used. The reduction of reinforcement in case of replacement by 369 tons (335 tonnes) of post-tensioning tendons can be calculated by

$$W_{RB} - W_{PT}$$
$$W_{RB} = 2.5W_{PT}$$

where W_{PT} is the total weight of post-tensioning tendons replaced; and W_{RB} is the total weight of reinforcing bars used. As a result, 1,108,925 lb (503,452 kg) of reinforcement can be reduced in this example.

Concrete

1) Slab

Post-tensioning tendons enable to reduce 2 in. (0.17 ft [51 mm]) of slab thickness per foot. For 450,000 ft² (41,806 m²) of the entire slab area, the amount of concrete reduction is

$$0.17 \text{ ft} \times 450{,}000 \text{ ft}^2 = 75{,}000 \text{ ft}^3$$
$$(50.8 \text{ mm} \times 41{,}806 \text{ m}^2 = 2124 \text{ m}^3)$$

2) Beam

The amount of concrete reduction in beams can be calculated by normalizing the volume by the spacing between beams in foot. While beam dimensions of 42 x 18 in. (1067 x 460 mm) are used with an 8 in. (203 mm) thick slab at intervals of 28 ft (8.5 m) for PT concrete beams, beam dimensions of 10 x 28 in. (254 x 711 mm) are used with a 10 in. (254 mm) thick slab at intervals of 18 ft (5.5 m) for RC beams. Hence, the normalized volumes of PT concrete beams and RC beams can be calculated by the following equations, respectively.

$$42 \text{ in.} \times (18 \text{ in.} - 8 \text{ in.}) \times L/28 \text{ ft} = 15L \text{ in.}^2/\text{ft}$$
$$(1.067 \text{ m} \times (0.460 \text{ m} - 0.203 \text{ m}) \times L/8.5 \text{ m} = 0.0323 \text{ m}^2/\text{m})$$

$$10 \text{ in.} \times (28 \text{ in.} - 10 \text{ in.}) \times L/18 \text{ ft} = 10L \text{ in.}^2/\text{ft}$$
$$(0.254 \text{ m} \times (0.711 \text{ m} - 0.254 \text{ m}) \times L/5.5 \text{ m} = 0.0211 \text{ m}^2/\text{m})$$

where L is the beam length.

3) Column

A column spacing of 40 x 28 ft (12 x 8.5 m) is required for the post-tensioned concrete while a column spacing of 20 x 18 ft (6 x 5.5 m) is required for reinforced concrete. Within a specific area of 40 x 252 ft (12 x 77 m), 20 columns are needed for the PT concrete, while 45 columns are needed for RC. Therefore, 800 and 1600 columns are needed for PT concrete and RC, respectively. Because the concrete dimensions of columns for PT concrete and RC are 30 x 30 in. (762 mm x 762 mm) and 24 x 24 in. (610 x 610 mm), respectively, with a height of 10 ft (3 m) in both cases, 14,000 ft³ (1300 m³) of concrete can be saved as follows

$$30 \text{ in.} \times 30 \text{ in.} \times 10 \text{ ft.} \times 800 \text{ columns} = 50{,}000 \text{ ft}^3$$
$$(762 \text{ mm} \times 762 \text{ mm} \times 3.048 \text{ m} \times 800 \text{ columns} = 1416\text{m}^3)$$

$$24 \text{ in.} \times 40 \text{ in.} \times 10 \text{ ft.} \times 1600 \text{ columns} = 64{,}000 \text{ ft}^3$$
$$(610 \text{ mm} \times 610 \text{ mm} \times 3.048 \text{ m} \times 1600 \text{ columns} = 1815\text{m}^3)$$

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