Carbon Emissions based on Ready-mix Concrete Transportation: A Production Home Building Case Study in the Greater Phoenix Arizona Area

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There is significant focus on sustainable development and green building in the construction industry. The problem is the lack of metrics to determine what is improvement and what is not. Measurement of the carbon emission provides one way to quantify and improve the environmental performance of construction operations. This study quantifies carbon emission for ready-mix concrete transportation and installation in the production home building domain. Data collection was completed from a concrete trade contractor and ready-mix concrete suppliers in the Greater Phoenix Arizona area. Influence of two production parameters, namely, 'slab size' and 'distance from subdivision to concrete plant' on carbon emission was studied using what-if scenario analysis. Further, the aggregate level carbon emission in the Greater Phoenix area has been quantified.

Key Words: production home building, ready-mix concrete transportation, carbon emissions and sustainable construction

Introduction

Production Home Building in the Phoenix Arizona Area

Production home building involves the construction of 50 to 100 similar lots or homes on a tract of land called a subdivision. Production homes are similar with respect to their basic configuration but have variations in terms of models and options. Production homes typically built in the Phoenix area consist of a post-tensioned concrete slab-on-ground foundation and wood framed construction. Construction of a production home consists of two major phases: land development and vertical construction. Land development involves building the horizontal infrastructure required at the subdivision level, including site excavation, retaining walls, perimeter walls, dry and wet utility lines, roads and landscaping (Centex Homes 2006). The vertical construction of a production home consists of 10 to 12 major phases, 90 to 100 different activities, 30 to 40 specialty trade contractors and code compliance inspections performed by city-building inspectors and third-party inspectors (Bashford et al 2003).

Examples of vertical construction phases completed by specialty trade contractors include concreting, plumbing, framing, drywall, siding/stucco, roofing, HVAC, electrical, doors and windows, painting, carpeting, counter tops, and fencing (Maracay Homes 2006, Engle Homes 2006). Among these phases, the framing and the concreting phases are the top two cost components and they account for 29% and 14% of the total cost of a production home respectively (HRI, 2006). The concreting phase is the first vertical construction phase of a production home and involves transportation of heavy materials and equipment. For example, the concreting phase of a typical production home requires the transportation of 30 to 60 tons of aggregate base course (ABC), 75 to 100 CY of ready-mix concrete, 0.5 to 1 ton of steel and a concrete pump.

The completion of the concreting phase involves a concrete trade contractor and several sub-trade contractors as well as material and equipment suppliers including: (1) construction crew, quality control inspector and superintendent of the concrete trade contractor; (2) ABC supplier; (3) ABC grading contractor; (4) post-tension cable sub-trade; (5) concrete pump supplier; (6) ready-mix concrete supplier; (7) superintendent of the home builder; (8) city building inspector and (9) third-party inspector. Among these, the ready-mix concrete supply is found to be one of the most significant components in terms of fuel consumption and carbon emissions.

Carbon Emissions

Recently, there is significant emphasis on green house gas emissions due to global warming and climate change. Carbon emissions (CO_2) represented 74% of the total global green house gas emissions in the year 2000 (US EPA 2008a). Several initiatives have been taken at the government, organization and individual level to reduce carbon emissions. For example, the national objective in the United States is to reduce the green house gas emissions by 18% in the 10 year time period 2002 to 2012 (US EPA 2008b). In the construction industry, there is increased awareness on sustainable development and green building. For example, the US Green Building Council (USGBC) developed 'Leadership in Energy and Environmental Design' (LEED) rating system to quantify the environmental performance of building construction. LEED rating is based on several factors such as site selection, water efficiency, energy and atmosphere, materials and resources use and indoor environmental quality (USGBC 2008). An initiative undertaken by construction firms primarily focuses on the use phase of the building. For example, a typical large scale home builder attempts to improve the environmental performance of homes through energy efficient heating, ventilation, and air-conditioning (HVAC) systems, better insulation, high performance windows, tight sealing to avoid air leakage, tight air ducts and the use of Energy Star appliances (Centex Homes 2008). Further, online software tools were developed to quantify the carbon emissions at the individual level (Scientific American 2008, BIE 2008, Earth lab 2008).

Previous studies on sustainable construction and green building primarily focused on achieving energy efficiency in the use phase, minimizing wastes and recycling/reuse of materials. Few studies emphasized the significance of environmental impact of onsite construction operations (Cole, 2000; Bilec et al 2006; Guggemos and Horvath 2006). Transportation is one of the significant components causing green house gas emissions. The Intergovernmental Panel on Climate Change (IPCC) 2007 report on climate change and mitigation states that the transportation sector accounted for 23% of the world's green house gas emissions in the year 2004 (IPCC 2008). Given the fact that the carbon tools are expected to be part of the green building design in the construction industry (Hunter 2008), this study focuses on the quantification of carbon emissions for ready-mix concrete transportation.

Objectives and Scope

The following are the objectives of this study:
(1) Quantify carbon emissions for ready-mix concrete transportation in production home building.
(2) Identify the production parameters that influence carbon emissions
(3) Perform what-if analysis based on production parameters and suggest guidelines for minimizing carbon emissions

The scope of this study is limited to the transportation of ready-mix concrete from the concrete plant to the construction site (subdivision). Ready-mix concrete supply for a post-tensioned slab foundation with 9" slab thickness is considered. Carbon emissions due to indirect supply chain components such as manufacturing of concrete trucks or transportation of aggregates, cement and water to the concrete plant are not included.

Methodology

The methodology for this study consists of the following steps:
1. Quantify the volume of ready-mix concrete (in cubic yards) per production home as a function of concrete slab size
2. Find the number of trips made by concrete trucks using the volume of the concrete and the truck capacity
3. Contact the ready-mix concrete supplier to obtain fuel consumption data (fuel efficiency in miles per gallon)
4. Find the minimum, average and maximum travel distances from the concrete plant to the subdivision in the Greater Phoenix area. This will be computed including the operational constraints within which ready-mix concrete is supplied
5. Compute the fuel consumption required for ready-mix concrete transportation per lot as a function of concrete slab size (in square feet) and distance to the concrete plant
6. Compute carbon emissions using the fuel consumption data and emission guidelines
7. Perform what-if scenario analysis to study the effect of home buyer choice and the selection of concrete supplier and the concrete plant

8. Demonstrate the impact at the aggregate level
9. Suggest guidelines to minimize the carbon emissions due to ready-mix concrete transportation

Data Collection

Data was collected from one large concrete trade contractor and ready-mix concrete suppliers in the Greater Phoenix area. Data includes: (i) concrete quantity and slab size for 110 lots; (ii) minimum, average and maximum travel distances from the concrete plant to the subdivision; (iii) ready-mix concrete truck capacity in cubic yards (CY); and (iv) fuel consumption data for ready mix concrete trucks.

Concrete volume and number of trips

The actual quantity of concrete placed for 110 lots was collected from the concrete trade contractor (SCP Construction 2008). These samples are based on post-tensioned slab foundations with 9" slab thickness. A regression analysis for these 110 samples resulted in Equation 1, which shows the relationship between the concrete quantity and the size of the floor slab with 9" slab thickness ($R^2 > 0.95$).

$$Y = 0.02599 * X + 9.58 \qquad (1)$$

where, 'Y' refers to the actual quantity of concrete placed for floor slab and outside flatwork in CY (excluding driveways and sidewalks) and 'X' refers to the concrete slab size in square feet

The variation in the concrete volume (in CY) as a function of slab size (varying from 1500 sqft to 5000 sqft) is presented in Table 1. The average concrete quantity for driveways and walks was found to be 9 CY. The number of trips made by concrete trucks from the concrete plant to the jobsite was determined using the total quantity of concrete placed and the truck capacity. The capacity of the typical ready-mix concrete truck is 10.5 cubic yards. Calculated number of trips is rounded to obtain the actual number of trips with a resolution of 0.5. If the concrete quantity needed in the last trip is less than or equal to half of the concrete truck capacity, it is assumed that concrete is supplied to two lots in the same trip.

Table 1: Slab size, concrete volume and number of trips

Concrete slab size (sqft)	Ready-mix concrete volume (CY)		Total volume of ready-mix concrete (CY)	Number of trips
	Concrete slab	Drive and walk		
1500	48.57	9	57.57	5.5
2000	61.56	9	70.56	7.0
2500	74.56	9	83.56	8.0
3000	87.55	9	96.55	9.5
3500	100.55	9	109.55	10.5
4000	113.54	9	122.54	12
4500	126.54	9	135.54	13
5000	139.53	9	148.53	14.5

Distance from the concrete plant to subdivisions

In order to find the minimum, average and maximum travel distances from the concrete plant to the subdivision, a total of 16 subdivisions and 20 ready-mix concrete plants were selected. These subdivisions and concrete plants are located in different parts of the Greater Phoenix area – for example, north west region, south east region and south west region. Based on the interaction with the concrete trade contractor, it was found that the ready-mix concrete is not always supplied from the closest concrete plant due to factors such as availability of concrete and trucks with a particular supplier and the type of concrete ordered. Further, it frequently occurs in practice to supply concrete from multiple plants for the same lot. To take these conditions into account, travel distances were computed for each subdivision based on the assumption that concrete will be supplied on a random basis from any one of the four concrete plants closest to the subdivision. Based on this calculation, Figure 1 shows a histogram for travel distances from the subdivision and concrete plant. Further, the average travel distance was found to be 15 miles.

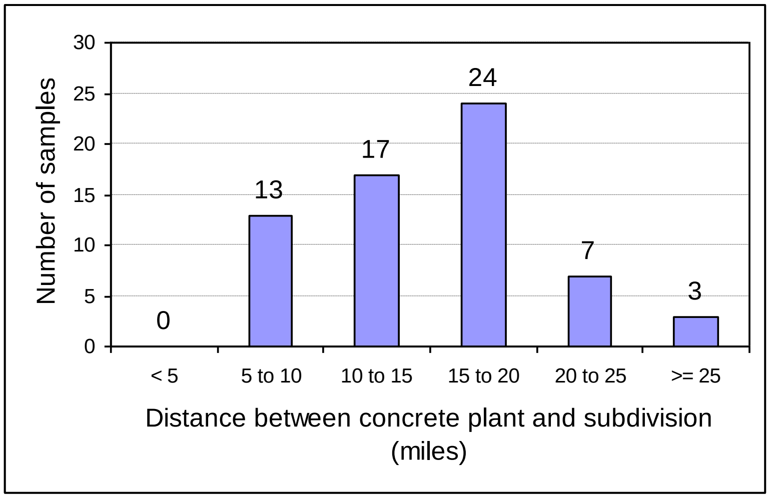

Figure 1: Histogram: travel distance and the number of samples

Fuel consumption of concrete truck

The following information was collected from a large scale ready-mix concrete supplier in the Greater Phoenix area and is based upon 2007 operations.

- Type of fuel used: Diesel
- Fuel efficiency for empty truck (miles per gallon): 3.3
- Fuel efficiency for loaded truck (miles per gallon): 2.8
- Average fuel efficiency per trip (miles per gallon) assuming that the travel and return distances are the same: 3.05

Analysis and Results

Carbon emissions calculation for a base scenario

The following example demonstrates the calculation of carbon emissions for a particular lot with a slab size of 2100 square feet:

1. Concrete slab size: 2100 square feet
2. Total concrete quantity (cubic yards): 73.16 [64.16 CY for slab and 9 CY for drive and walk]
3. Truck capacity: 10.5 CY
4. Number of trips: 73.16 / 10.5 = 7
5. Distance from concrete plant to subdivision: 15 miles
6. Fuel consumption per trip: (2 X 15) / 3.05 = 9.84 gallons of diesel
7. Fuel consumption per lot: 7 X 9.84 = 68.88 gallons
8. Carbon emissions: 22.23 lb of CO_2 per gallon of diesel (US EPA 2005)
9. Carbon emissions per lot: 68.88 X 22.23 = 1531.20 lb of CO_2

Influence of slab size

The slab size was varied from 1500 sqft to 5000 sqft and its influence on the total volume of concrete required, number of trips, fuel consumption per lot and carbon emissions (CO_2) per lot was calculated. The one way travel distance from the concrete plant to the subdivision was found to be 15 miles as explained above. Figure 2 shows the influence of slab size on carbon emissions per lot. Figure 2 indicates that fuel consumption and carbon emissions per lot increase by 67.72% when the slab size is doubled (i.e. from 1500 sqft to 3000 sqft). Home buyer influences the size of the home and the concrete slab. By choosing an optimal size, home buyer can minimize the concrete demand per home and associated carbon emission.

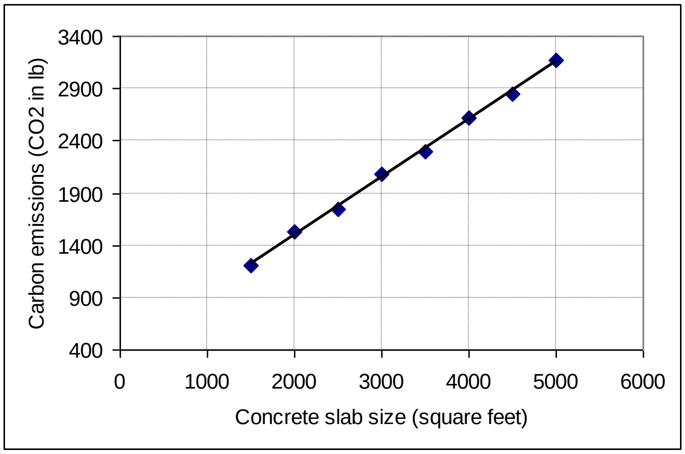

Figure 2: Influence of slab size on carbon emissions per lot

Influence of travel distance

The one way travel distance from the concrete plant to the subdivision was varied from 5 miles to 25 miles and its impact on the carbon emissions was studied (Figure 3). In this analysis, the slab size is kept constant and is assumed as 2100 sqft. Figure 3 shows that the carbon emissions increase by 100% when the travel distance is doubled. There is potential to reduce carbon emissions significantly by supplying ready-mix concrete from the closest concrete plant for each subdivision. For example, by supplying concrete from a plant located at 5 miles distance instead of another plant located at 15 miles distance, the following benefits can be realized (slab size 2100 sqft): reduces the total driving distance by 140 miles, saves 46 gallons of diesel and eliminates 1020 lb of CO_2 emissions per lot.

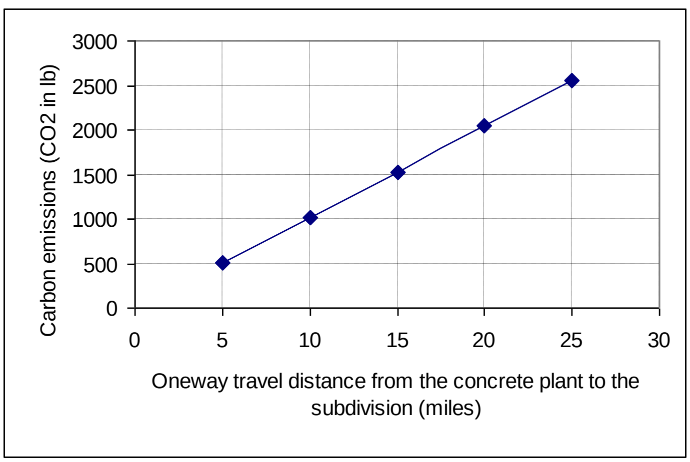

Figure 3: Influence of travel distance on carbon emissions per lot

Aggregate level impacts

Fuel consumption and carbon emissions were quantified at the aggregate level (for Greater Phoenix area) using a conservative assumption that the slab size is 2100 sqft and the one way travel distance from the concrete plant to the subdivision is 10 miles for all lots. Figure 4 shows the number of new single family home sales in the Greater Phoenix area from 1996 to 2006. Figure 5 shows the carbon emissions equivalent to Figure 4. Carbon emissions can be significant at the aggregate level. For example, carbon emission for the year 2005 is found to be 21,708.9 tons. This would have been reduced by 10,854.4 tons if a concrete plant is chosen within 5 miles distance for all lots. Thus, a small improvement at the lot level can result in significant benefit at the aggregate level in terms of fuel consumption and emissions.

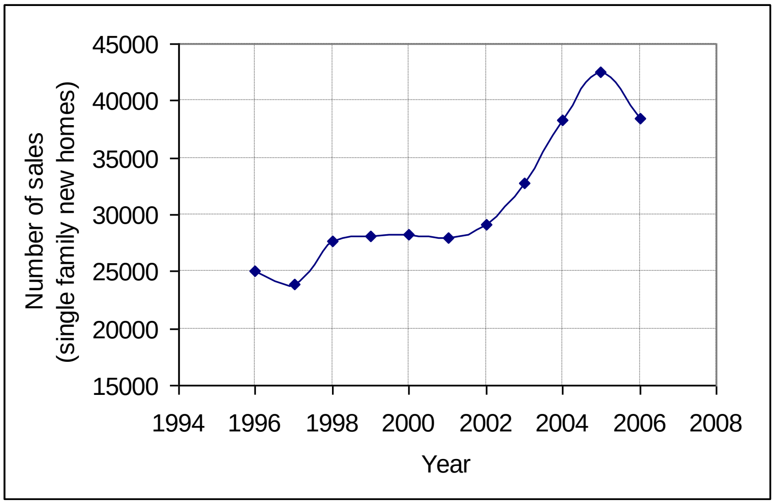

Figure 4: Number of new single family home sales in the Greater Phoenix area (ASU Realty Studies 2008)

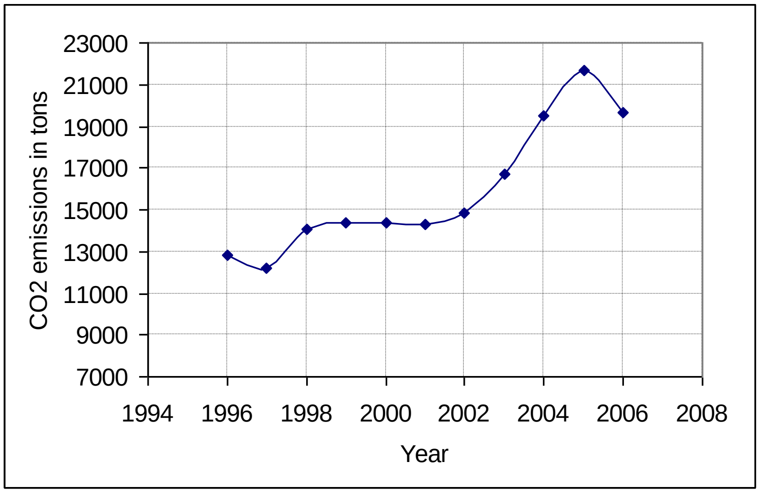

Figure 5: Carbon emissions for ready-mix concrete transportation equivalent to Figure 4 (slab size 2100 sqft and distance 10 miles)

Discussion and Conclusions

This study presents the quantification of carbon emission (CO_2) for ready-mix concrete transportation using a production home building case study from the Greater Phoenix Arizona area. Based on the data collection and analysis, this study finds that the following factors influence carbon emission: (1) slab size – which depends on the home size (2) distance from the subdivision to the ready-mix concrete plant and (3) truck type, fuel type and fuel efficiency of truck. What-if scenario analysis has been presented to show the influence of slab size and the travel distance on carbon emissions. Further, this study quantifies the variation in the aggregate level CO_2 emission for ready-mix concrete transportation from the year 1996 to 2006 in the Greater Phoenix area.

Results indicate that there is potential to achieve significant reduction in carbon emissions through careful selection of the two production parameters – concrete slab size and distance from concrete plant to subdivision. For example,

1. By minimizing the concrete slab size from 3000 sqft to 1500 sqft, fuel consumption and carbon emissions can be reduced by 40% per lot.
2. For a 2100 sqft slab size, choosing a concrete plant located at 5 miles distance instead of another plant located at 15 miles distance, reduces the transportation by 140 miles, saves 46 gallons of diesel and eliminates 1020 lb of CO_2 emissions per lot.

This study will be beneficial to concrete trade contractors and ready mix concrete suppliers to understand the influence of their operational practices on fuel consumption and carbon emission and improve the environmental performance. While the study may be considered idealistic, we found that the contractors who worked with us on this study were excited to discover the results of the study and they indicated these results will be useful to them in their project planning.

While it is obvious that a close concrete plant will result in less travel time and fuel cost, we found that concrete is not always supplied from the closest plant. Due to truck availability, concrete availability, and other factors, many times, concrete is supplied from a plant located at farther distance.

Carbon emission based on ready-mix concrete transportation can be minimized using the following guidelines:

1. Development of residential subdivisions in the form of master-planned communities; and selection of a ready mix concrete plant that is located closest to the subdivision.
2. Selection of optimal home size by the homebuyer just to meet their requirements. Residential homes with concrete slab size less than 2500 sqft can be given preference over larger size homes. Home buyer can select a home without basement to minimize the concrete demand and associated emission.

Further, alternate options in terms of vehicle type, engine power, truck capacity and fuel type could be investigated to improve the fuel efficiency of concrete trucks.

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