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Evaluation of the influence of creep and shrinkage determinants on column shortening in mid-rise buildings

Ali B-Jahromi[*1], Abdulazeez Rotimi[2a], Shivan Tovi[2a], Charles Goodchild[3b] and Joseph Rizzuto[4c]

[1]*Department of Civil Engineering, School of Computing and Engineering, University of West London, W5 5RF, London, UK*
[2]*School of Computing and Engineering, University of West London, W5 5RF, London, UK*
[3]*The Concrete Centre, SW1V 1HU, London, UK*
[4]*Department of Civil Engineering, School of Computing and Engineering, University of West London, W5 5RF, London, UK*

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Abstract. The phenomenon of concrete column shortening has been widely acknowledged since it first became apparent in the 1960s. Axial column shortening is due to the combined effect of elastic and inelastic deformations, shrinkage and creep.

This study aims to investigate the effects of ambient temperature, relative humidity, cement hardening speed and aggregate type on concrete column shortening. The investigation was conducted using a column shortening prediction model which is underpinned by the Eurocode 2.

Critical analysis and evaluation of the results showed that the concrete aggregate types used in the concrete have significant impact on column shortening. Generally, aggregates with higher moduli of elasticity hold the best results in terms of shortening. Cement type used is another significant factor, as using slow hardening cement gives better results compared to rapid hardening cement. This study also showed that environmental factors, namely, ambient temperature and relative humidity have less impact on column shortening.

Keywords: concrete; creep and shrinkage; mid-rise buildings; column shortening

1. Introduction

In high-rise concrete buildings, columns are subject to axial shortening due to the combined effect of elastic and inelastic deformations, shrinkage and creep (Concrete Society 2008). This phenomenon, noticed for the first time in the 1960s takes place during the curing of freshly cast concrete as well as on a longer-term basis throughout a building’s life span (Moragaspitiya *et al*. 2010). Several factors affect column shortening: these include the concrete properties and amount

*Corresponding author, Associate Professor, E-mail: Ali.Jahromi@uwl.ac.uk
[a]Ph.D. Candidate
[b]Principal Structural Engineer, E-mail: cgoodchild@concretecentre.com
[c]Professor, E-mail: j.rizzuto@uwl.ac.uk

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of steel reinforcement, variations in Young's modulus of elasticity of the concrete, environmental conditions and the ratios of cross-sectional area to length (Moragaspitiya 2011).

Concrete is a heterogeneous material with mechanical and rheological properties that change with time. Creep and shrinkage have paramount importance in the design of concrete mid-rise and high-rise structures especially as the total shortening of a column comprises the sum of immediate axial deformations and the induced creep and shrinkage deformations (Pan *et al*. 1993).

Concrete as a material is one of the most widely used owing to its durability, ease of construction and low cost (Shaikh and Taweel 2015). Several shrinkage and creep prediction methods have been developed to estimate the time-dependent deformations of concrete structures such as axial and differential column shortening as the inaccurate prediction of these phenomena could lead to structural and non-structural failures especially with increasing building height (Moragaspitiya 2010, Zou *et al*. 2014). Therefore, it is vital that time-dependent deformations of vertical elements of hardened concrete structures are predicted and appropriate adjustments are made to the construction system used in high-rise buildings in order to cater for these deformations (Njomo and Ozay 2014). Creep and shrinkage are affected by numerous factors related to both the design and the construction of a concrete structure that make it difficult to get an in-depth understanding of the physical processes that cause creep and shrinkage of concrete elements (Aslani 2015). However, many studies have been carried out on the subject that have determined the main mechanisms that govern the rheological behaviour of cured concrete as well as the parameters that influence their magnitudes. Numerous models have been developed for the prediction of creep and shrinkage: some of them are regulatory such as the Eurocode 2 Model, which is based on the CEB-FIP MC90 model, and the ACI-209 model developed by the American Concrete Institute (Zou *et al*. 2014). The precision and accuracy of these models however are low, especially for longer term behaviour (Bazant and Baweja 1995).

Differential axial shortening of columns induces additional stresses in horizontal structural members such as beams and slabs, and vertical non-structural members such as partition walls and glazing (Pan *et al*. 1993). These induced additional stresses increase bending moments, shear forces or torsional moments, affecting thereby the corresponding diagrams used for the ultimate limit state design of the structure. Therefore, it is important that engineers can accurately quantify the shortening of columns in order to produce accurate structural designs for buildings susceptible to column shortening effect. Through the review of existing literature on differential column shortening in concrete structures, including creep and shrinkage deformations, no specific statements were evident on the exact impact that each of the factors affecting shrinkage and creep have on column shortening. The Concrete Centre has produced Excel (Microsoft 2016) spreadsheets underpinned by Eurocode 2, for the prediction of column shortening with the possibility of selecting ambient temperature, relative humidity, cement type and aggregate type. The aim of this study is to investigate and quantify the effect each of these factors and parameters on column shortening (The Concrete Centre 2016).

2. Review of column shortening developments

Shortening of concrete columns induce additional stresses and torsion in slabs and beams. This is due to the differential shortening of the columns, in other words, the columns supporting a beams and slab system do not shorten by the same amount as they might not be subject to the same stress levels (Fintel *et al*. 1987). This can be easily pictured when comparing the vertical loads

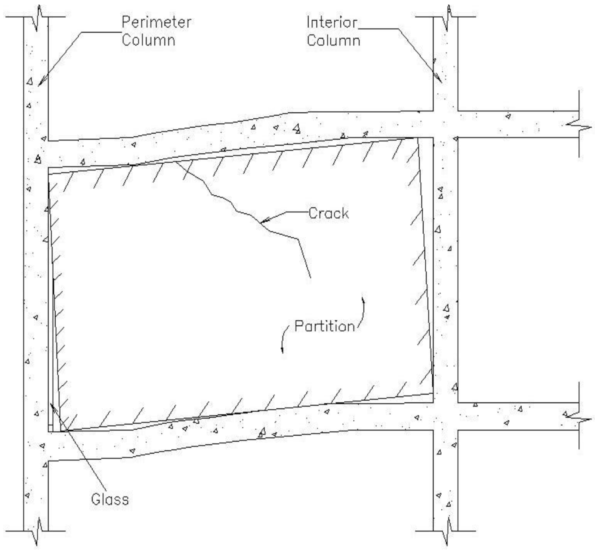

Fig. 1 Torsional effect of differential column shortening (reproduced from SlideShare 2016)

acting on internal columns to those acting on perimeter columns. A perimeter column typically supports two beams when it is located in the corner of the building and three beams otherwise, whereas an internal column typically supports four beams. The loads on perimeter columns are thus generally lower than the loads on internal columns, hence the difference in mechanical deformations of the columns. The differential aspect of column shortening is thus caused by the variations that are inherent to the structural design of a column, hence the need of considering this phenomenon during the design stage and also proffer means of reducing differential column shortening. Plain non-differential column shortening also have adverse effects on the cladding and heads of partitions where allowance for the axial shortening has not been provided for (The Concrete Centre 2014).

Fig. 1 illustrates the torsional effects of differential column shortening impact on non-structural members such as partition walls and façade glazing.

In order to predict and monitor axial shortening, engineers have used analytical procedures, laboratory tests and measurements on constructed buildings along with analytical procedures. However, by comparing analytical predictions with on-site observations, it has been found that the accurate prediction of this phenomenon is difficult to achieve and complex. This is due to the variability, complexity and to some extent, the unpredictability of the influencing factors (Baidya and Mendis 2010).

The American Concrete Institute Committee report 209 (2008) noted that regulatory models presented in European and American codes are based on past experience and they present a compromise between the accuracy of the results and the ease of use. Furthermore, the uncertainties of these models emanate from the fact that they consider a broad range of materials with different characteristics and from different countries in order to be applicable in all the regions where these codes are used (ACI Committee 209 2008). Additionally, it has been shown that within the same batch of concrete, the shrinkage and creep of the specimens varied by up to 8%, justifying thereby the unpredictability of creep and shrinkage (Bazant *et al*. 1987). Also, the development of models for the prediction of creep is difficult because the theory and processes describing it are not completely understood. According to Gardner (2004), it is not possible to predict creep and shrinkage with an accuracy of +/-20%. The Creep and Shrinkage Committee from the ACI could not reach a consensus to determine which model allows for the most accurate prediction. The debate is partly on the type of data one should consider to develop the models, on the types of parameters to be used in the model equations and on the appropriate statistical methods for the comparison of the models (ACI Committee 209 2008).

According to Moragaspitiya (2011), shear cores and columns under axial compression are the main structural members for axial shortening control. The design of these elements is thus the stage at which the issue of column shortening should be considered. Some of the methods that could be used to reduce the shortening of the columns include improvement of the mechanical properties of the materials and structural members, the use of rigid joints to connect columns and horizontal members, outriggers and the increase of reinforcement in the columns (Hansoo and Seunghak 2014). However, the shortening of columns is usually investigated once the design of the structural elements is complete, making it laborious to address by structural element design alterations, that is, changing the column sections and material properties. Nonetheless, the reinforcement bars can be increased in order to stiffen the column and reduce its shortening (Hansoo and Seunghak 2014).

Patel and Pooojara (2014)-carried-out a construction stage analysis using the Extended Three-Dimensional Analysis of Building Systems (ETABS) software (Computer and Structures, Inc 2012), to show that the cross-sectional area of columns had a direct impact on the differential shortening of the columns. The study demonstrated that the larger columns exhibits lower axial and differential shortenings (Patel and Poojara 2014). The study additionally found that when the construction pace is high, the shortening of the columns is substantial for both tall and short buildings; nevertheless, when the construction rate is low, short buildings are not concerned with column shortening.

Acker (2003), found that creep strains in concrete result only from the visco-plastic behaviour of cement hydrates C-S-H; viscous deformations outweighing by far the elastic deformation, and this deformation is completely reversible. This finding is the result of creep tests and indentation at the nanoscale on a high-performance fibre reinforced concrete. A comparative study of the basic creep behaviour was made between different types of concrete. These included ordinary concrete, high and ultra-high performance concrete and fibre reinforced concrete. The outcome showed the differences between the basic creep values of different concretes. The study concludes that these differences can be explained by a profound change in the internal structure of the hydrates C-S-H. To explain this change, there are two theories. The first is the “exhausted collapse site” created by shrinkage. Whereas, the second is linked to a coupling between capillary pressure and the mechanical stress or, in how these stresses are superimposed locally at the hydrate layer or, in the process of stress concentration and capillary pressure that occurs in dry granular stacks (Acker 2003).

Hansoo and Seunghak (2014), worked on the reduction of differential column shortening in tall buildings. They showed that increasing the reinforcement in the columns results in decreased differential shortening. Their study was carried out by modelling an 80-storey building with beam spans of 8 m and by taking the beam stiffness as zero. Their results demonstrated that an increase of 4% in the steel ratios of the columns lead to a column shortening reduction of 51.7% and that for a 1% increase in reinforcement the column shortening was reduced by 15.9%. However, the work also showed that the effect of increasing the steel ratio on the shortening of the columns is not linear and it decreases with higher steel ratios.

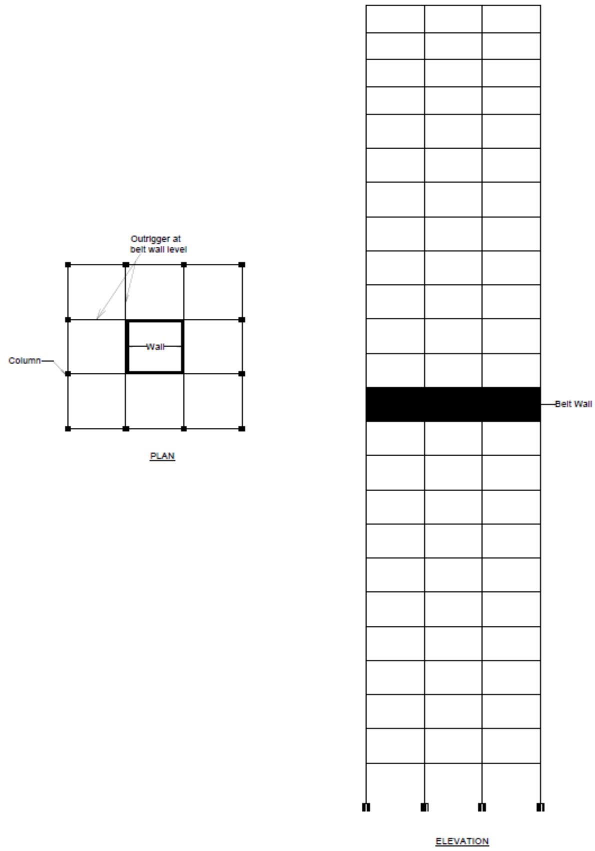

Fig. 2 Outrigger system

Choi *et al*. (2012) and Kamath *et al*. (2015) investigated a different approach for reducing differential column shortening in tall buildings with the use of outriggers. Outriggers are used to connect core walls to peripheral columns as illustrated in Fig. 2. The use of these rigid horizontal structural members increases the stiffness of the structure thereby reducing its overturning ability (Choi *et al*. 2012). Both studies found that optimal use of outriggers can significantly reduce differential axial shortening of concrete columns. Moreover, Kamath *et al*. (2015), results showed that the differential shortening was decreased by 34% when an outrigger system was used at a level 58.3% of the height of the building. Higher overall height to outrigger position height ratios produced an increase of the differential shortening. Additionally, using the same model while keeping the outrigger fixed at its optimum position of 58.3% of the overall height and by adding another outrigger system at an optimum position of 75% of the structure's height, the differential shortening was reduced by a total of 58% (Kamath *et al*. 2015).

3. Column shortening prediction

For the purposes of this study, the behaviour of a 12-storey and a 24-storey building structure was simulated using the TCC55 and TCC55X Excel (Microsoft 2016) spreadsheets produced by

Table 1 Geometry and loading sequence of the 12-Storey building

Level	Time gap days	Column below					Col *SW* kN	Floor *SW* kN	At age days	Balance of G_k kN	Age days	Perm Imposed Q_k kN	Age days
		f_{ck} N/mm^2	Length mm	*H* mm	*B* mm	A_{SL} mm^2							
Roof	14	40	3750	300	300	452	8.4	354.4	7	118.1	28	44.3	82
11	14	40	3750	300	300	1257	8.4	354.4	7	118.1	28	62.0	96
10	14	40	3750	400	400	1257	15.0	354.4	7	118.1	28	62.0	110
9	14	40	3750	450	450	1257	19.0	354.4	7	118.1	28	62.0	124
8	14	40	3750	450	450	1963	19.0	354.4	7	118.1	28	62.0	138
7	14	60	3750	450	450	1257	19.0	354.4	7	118.1	28	62.0	152
6	14	60	3750	450	450	2592	19.0	354.4	7	118.1	28	62.0	166
5	14	60	3750	500	500	3217	23.4	354.4	7	118.1	28	62.0	180
4	14	60	3750	500	500	3217	23.4	354.4	7	118.1	28	62.0	194
3	14	80	3750	500	500	3217	23.4	354.4	7	118.1	28	62.0	208
2	14	80	3750	500	500	3217	23.4	354.4	7	118.1	28	62.0	222
1	14	80	4500	500	500	4825	28.1	354.4	7	118.1	28	62.0	236

Where: f_{ck}=Characteristics cylinder strength of concrete; *H*=Column depth; *B*=Breadth of column; A_{SL}=Area of steel; *SW*=Selfweight; G_k=Characteristics value of permanent action and Q_k=Characteristics value of variable action

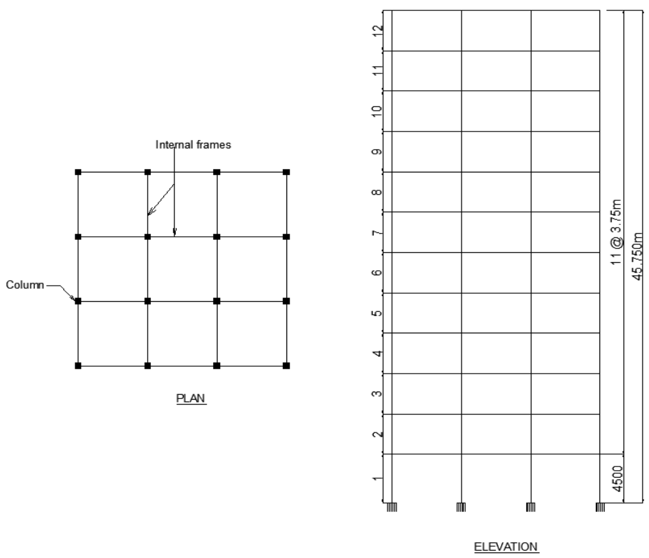

Fig. 3 12-storey building frame

The Concrete Centre (The Concrete Centre 2016), for the prediction of column shortening. These Concrete Centre spreadsheets calculate both the short-term and long-term shortenings of columns based on Eurocode 2 for creep and shrinkage strain. It evaluates shortening from the roof downwards and considers that time step zero equates to construction of the lowest column; it also computes time-dependent creep and shrinkage factors by allowing for detailed construction history

Table 2 Geometry and loading sequence of the 24-Storey building

Level	Time gap days	Column below f_{ck} N/mm^2	Length mm	H mm	B mm	A_{SL} mm^2	Col SW kN	Floor SW kN	At age days	Balance of G_k kN	Age days	Perm Imposed Q_k kN	Age days
Roof	14	40	3000	300	300	3619	6.8	300.6	7	93.8	28	14.4	133
23	14	40	3000	300	300	3619	6.8	300.6	7	93.795	28	14.4	147
22	14	40	3000	300	300	3619	6.8	300.6	7	93.795	28	14.4	161
21	14	40	3000	300	300	3619	6.8	300.6	7	93.795	28	14.4	175
20	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	154
19	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	168
18	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	182
17	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	196
16	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	210
15	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	224
14	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	238
13	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	252
12	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	266
11	14	40	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	280
10	14	48	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	91
9	14	48	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	105
8	14	48	3750	300	300	3619	8.4	601.3	7	187.59	28	28.9	119
7	14	48	3750	300	300	6283	8.4	601.3	7	187.59	28	28.9	133
6	14	48	3750	300	300	9817	8.4	601.3	7	187.59	28	28.9	147
5	14	48	3750	300	300	16085	8.4	601.3	7	187.59	28	28.9	161
4	14	48	3750	300	300	16085	8.4	601.3	7	187.59	28	28.9	175
3	14	48	3750	300	300	19302	8.4	601.3	7	187.59	28	28.9	189
2	14	48	3750	300	300	24127	8.4	601.3	7	187.59	28	28.9	203
1	14	48	4500	500	500	27344	28.1	601.3	7	187.59	28	28.9	217

*See Table 1 for symbols notation

to inputted (The Concrete Centre 2016). The short-term shortening is referred to as 'Shortenings between Floors' and represents the amount by which a column lift shortens in length when the next floor is constructed on top of it. Whereas, the long-term shortening is referred to as 'Floor Displacements' and represents the net displacement of the floor from the level at which it was erected (The Concrete Centre 2016).

3.1 Experimental design

The column shortening effect can be determined by considering the variation of possible parameter combinations. The parameters are: (i) ambient temperature, (ii) relative humidity, (iii) cement hardening speed and (iv) types of aggregate used. The considered ambient temperatures are 5°, 20° and 30° Celsius along with relative humidity (RH) of 50%, 60%, 70% and 80%.

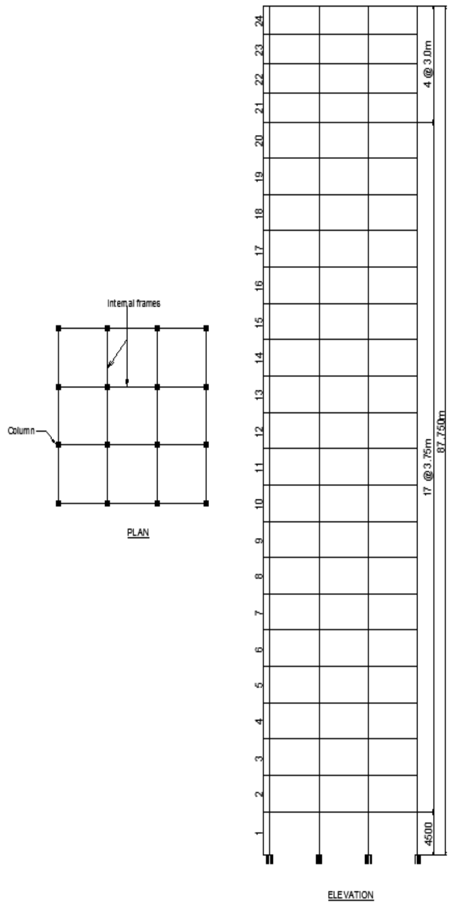

Fig. 4 24-storey building frame

Additionally, Slow-, Normal-, or Rapid hardening (S, N or R) cement classes based on Eurocode 2 classification are considered along with four aggregate mineralogy types, namely: Basalt, Limestone, Quartzite and Sandstone. The variation of possible parameter combinations was investigated on two types of structure, that is, 12-storeys and 24-storeys and the result of the long term column shortening effect is presented.

3.2 Building description

3.2.1 12-Storey building

The TCC55 Excel spreadsheets produced by the Concrete Centre allows for the calculation of the shortening of the columns for structures up to 12-storey (45.75 m total height) in terms of creep and shrinkage strains in accordance with BS EN 1992-1-1 Clauses 3.1.3(1), 3.1.3. (3) and Annex B.

For this study, the dimensions of the columns, the concrete strength, the area of steel reinforcement, as well as the loading sequence for the 12-storeys are shown in Table 1; Fig. 3 shows the structure's frame.

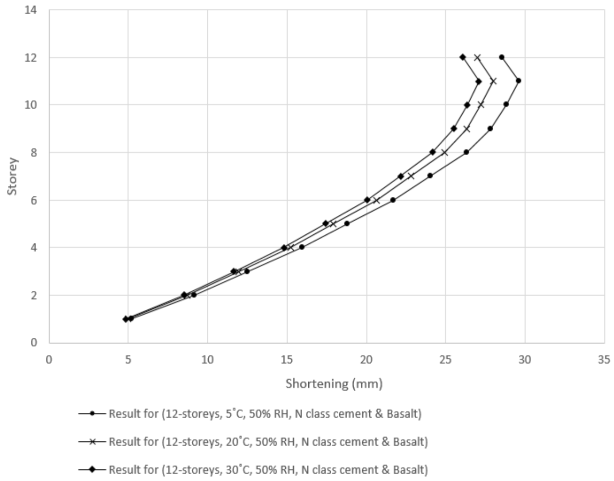

Fig. 5 Ambient temperature simulation results for 12-storey building structure. See Table 1

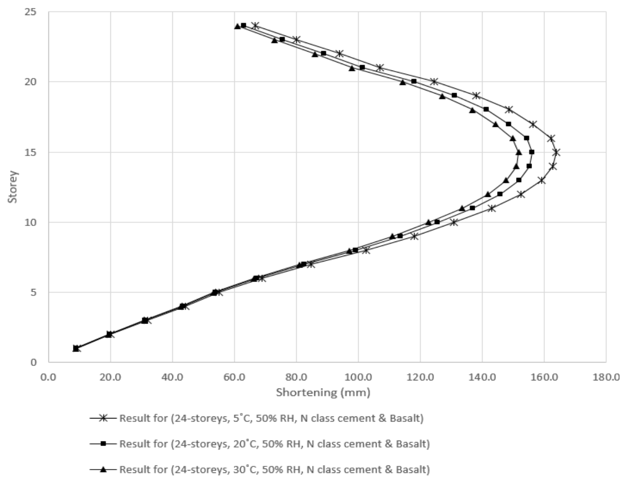

Fig. 6 Ambient temperature simulation results for 24-storey building structure. See Table 2

3.2.2 24-storey building

The Concrete Centre TCC55X Excel spreadsheet calculates the shortening of the columns for structures up to 24-storeys. The dimensions of the columns, the concrete strength, the area of steel reinforcement used and the loading sequence for the 24-storey structure (87.75 m total height) used in this study are shown in Table 2; Fig. 4 shows the structure's frame.

4. TCC55 and TCC55X results and discussion

4.1 Investigation of the effects of environmental factors on column shortening

4.1.1 Ambient temperature

It has been observed during the simulations that higher ambient temperatures resulted in lower

Table 3 Results summary for the effect of ambient temperature on column shortening

50% RH, N Type Cement, Basalt aggregate	5℃	30℃	Δ (mm)	Δ (%)	Δ/1℃
Shortening at 11th Floor for 12-Storey	29.6	27.1	2.5	9	0.10
Shortening at 15th Floor for 24-Storey	163.8	151.6	12.2	7	0.49

Δ=Difference in shortening

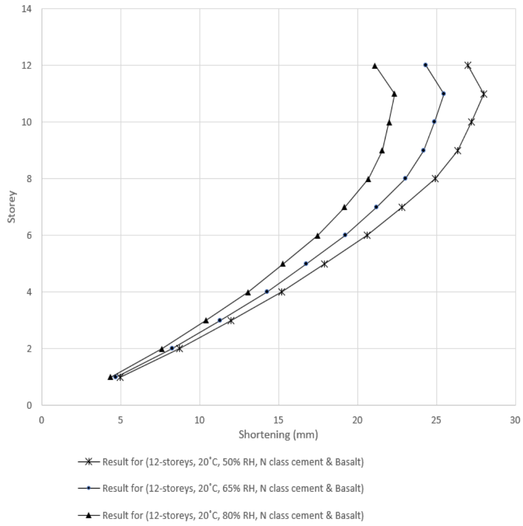

Fig. 7 Relative humidity simulation result for 12-storey building structure. See Table 1

shortenings of the columns. For instance, in the 12-storey building with an ambient temperature of 5℃, 50% relative humidity, N class cement, and Basalt used as aggregate, the total net shortening that would occur at roof level is 28.6 mm as shown in Fig. 5, whereas whilst keeping the same conditions but raising the ambient temperature to 30℃, the total shortening at roof level decreases to 26.1 mm. However, the maximum values for total net shortening are reached at the 11th floor with a total of 29.6 mm at 5℃, 28 mm at 20℃ and 27.1 mm at 30℃.

Fig. 6 shows that a similar trend is also observed in the case of the 24 storey building; where a total net shortening of 66.7 mm is predicted at the 24th floor level with 5℃ ambient temperature, 50% relative humidity, N class cement and Basalt used as aggregate. A total shortening of 60.7 mm is obtained at the 24th floor level with identical conditions but with 30℃ ambient temperature.

A predicted maximum shortening of 163.8 mm, 156.1 mm and 151.6 mm occurring at the 15th floor for 5℃, 20℃ and 30℃ ambient temperatures respectively.

For both the 12 and 24-storey structures, it is observed that when all of the other variables are kept constant, a 9% to 7% reduction in maximum shortening respectively occurs when the ambient temperature increases from 5℃ to 30℃.

As shown in Table 3, there is an increase of 0.10 mm in total net column shortening for each 1℃ ambient temperature drop for the 12-storey building and an increase of 0.49 mm for each 1℃ ambient temperature drop for the 24-storey building.

4.1.2 Relative humidity

The Concrete Centre considers a relative humidity of 50% as 'Internal Exposure' and a relative

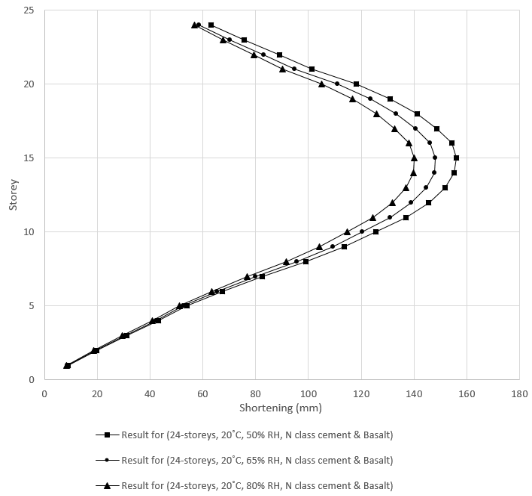

Fig. 8 Relative humidity simulation results for 24-Storey building structure. See Table 2

Table 4 Results summary for the effect of relative humidity on column shortening

20℃, N Type Cement, Basalt aggregate	50% RH	80% RH	Δ (mm)	Δ (%)
Shortening at 11th Floor for 12-Storey	28.0	22	6.0	20
Shortening at 15th Floor for 24-Storey	156.1	140.1	16.0	10

humidity of 80% as ‘External Exposure’ (The Concrete Centre 2016). However, relative humidity should be considered as the amount of water vapour present in the air in relation to the overall amount of water vapour that the air can hold at a specific temperature (The Concrete Countertop Institute 2016).

The simulation results show that the higher the relative humidity the lower the shortening. This can probably be attributed to the fact that less water is lost by the concrete at higher relative humidity, thereby resulting in lower plastic shrinkage effect. As shown in Fig. 7, in the case of the 12-storey building, with an ambient temperature of 20℃, 50% relative humidity, N class cement, and Basalt used as aggregate, the maximum total net shortening that was obtained at the 11th floor level was 28.0 mm whereas, a maximum total net shortening of 22.3 mm was obtained with 80% relative humidity.

In the 24-storey building a maximum total net shortening of 156.1 mm was obtained at the 15th floor level with 50% relative humidity. Whereas with 80% relative humidity the maximum total net shortening at the 15th floor was 140.1 mm. The results show a 10% reduction in net maximum shortening when relative humidity is increased from 50% to 80%. Fig. 8 illustrates relative humidity results for the 24-storey building structure.

Generally, the higher the relative humidity, the less water can evaporate from the freshly cast concrete, this results in a slower concrete curing rate that consequently produces a higher compressive strength concrete. As creep and shrinkage related strains are directly related to the concrete compressive strength, it is expected that creep and shrinkage deformations increase with decreasing compressive strengths and vice versa.

From Table 4, it is apparent that the total net shortening of the columns can be reduced by 20% to 10% for the 12-and 24-storey building by increasing the relative humidity from 50% to 80%.

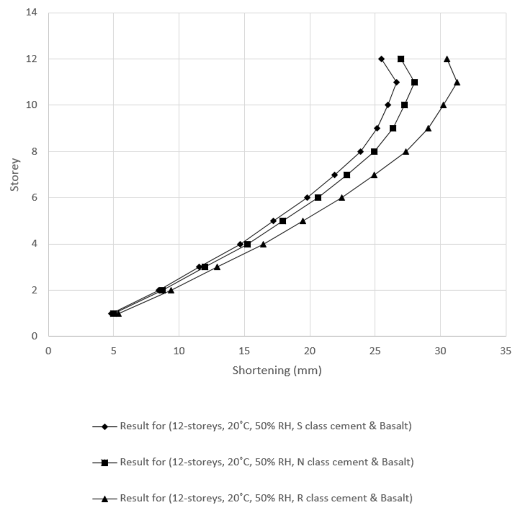

Fig. 9 Slow, normal and rapid hardening cement results for 12-storey building structure. See Table 1

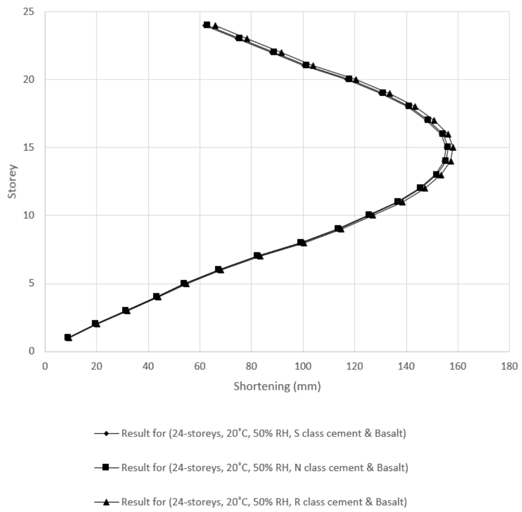

Fig. 10 Slow, normal and rapid hardening cement results for 24-storey building structure. See Table 2

4.2 Investigation of the effects of material parameters on column shortening

4.2.1 Cement classification

The Concrete Centre's prediction spreadsheets allow for 3 classes of cement to be used. The cement can be either of the three classes according to Eurocode 2: Slow-, Normal-, or Rapid hardening (S, N or R) cement; the expressions being in terms of rate of strength gain (British Standard Institution 2014). There are different types of cement available commercially however, in the UK these are based on designations CEM I, CEM II & CEM III (The Concrete Centre 2016). Generally, CEM I cements are Portland cements and will typically be Classification 'R' to BS EN 1992-1-1. CEM II and CEM III, or their equivalents, may be 'S', 'N' or 'R' (The Concrete Centre 2016).

Table 5 Results summary for the effects of cement type on column shortening

20℃, 50% RH, Basalt aggregate	S-Type Cement	Δ(N-S) (mm)	Δ(N-S) (%)	R-Type Cement	Δ(R-N) (mm)	Δ(R-N) (%)	N-Type Cement
Shortening at 11th Floor for 12-Storey	26.6	1.4	5	31.3	3.3	12	28.0
Shortening at 15th Floor for 24-Storey	155.4	0.7	0.4	158.1	2.0	1.3	156.1

S-Type=Slow hardening;
Δ(N-S)=(Normal hardening cement column shortening)-(Slow hardening cement column shortening);
N-Type=Normal hardening;
Δ(R-N)=(Rapid hardening cement column shortening)-(Normal hardening cement column shortening);
R-Type=Rapid hardening.

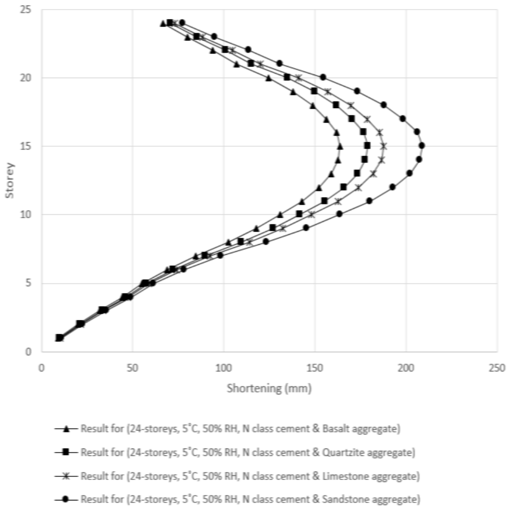

Fig. 11 Aggregate type results at 5℃, 50% RH, and normal hardening cement for the 24-storey building

As shown in Fig. 9, the simulation results indicate that the slower the hardening the less shortening occurs. For the 12-storey case, with 20℃ ambient temperature, 50% relative humidity and Basalt used as aggregate, the maximum total net shortening is obtained at the 11th floor level with values of 26.6 mm for 'Slow Hardening' cement, 28.0 mm for 'Normal Hardening' cement and 31.3 mm for 'Rapid Hardening' cement.

A similar trend is observed for the 24-storey building structure as illustrated in Fig. 10. The maximum total net shortening is observed at the 15th floor level with values of 155.4 mm for slow hardening cement, 156.1 mm for normal hardening cement, and 158.1 mm for rapid hardening cement. The effect of cement type on the maximum net shortening in the 24-storey building structure is not as significant as that predicted in the 12-storey building structure. In the 24-storey case, the maximum net shortening occurs at the 15th floor level. For the 12-storey building, the results show that net maximum shortening increases by approximately 5% and 16% for normal and rapid hardening cement respectively compared to that of slow hardening cement. Whereas, for the 24-storey building, the net maximum shortening increases by approximately 0.5% and 2% for normal and rapid hardening cement respectively compared to that of slow hardening cement.

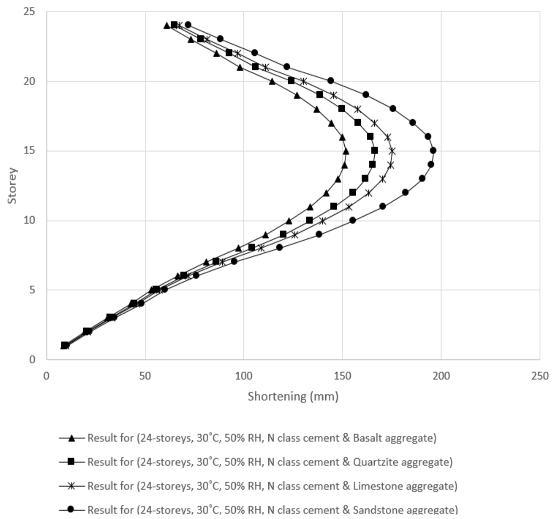

Fig. 12 Aggregate type results at 30℃, 50% RH, and Normal Hardening Cement) for the 24-Storey building

Table 5 shows that the faster the hardening of the cement, the higher the shortening effect especially for building structures not up to 24-storey. By choosing to use a slower setting cement, the total net shortening can be reduced by 5% and 0.4% for the 12-and 24-storey buildings respectively. Whereas, deciding to use a rapid setting cement, the total net shortening will be increased by 12% and 1.3% for the 12-and 24-storey buildings respectively.

4.2.2 Investigation of the effect of the mineralogy of the aggregate on column shortening

The Concrete Centre's spreadsheets allows for selection of four different types of aggregates, namely: Basalt, Limestone, Quartzite and Sandstone. The effect of using each of these types of aggregate has been investigated in all the environmental conditions as well as using the three types of cement available on the programme.

This study showed that irrespective of the ambient temperature, relative humidity and cement type used, the same aggregate type ranking emerges in terms of column shortening. The results obtained for the 24-storey building with an ambient temperature of 5℃, a relative humidity of 50% and N-class cement are shown in Fig. 11.

Fig. 11 presents the results of using a 'N' class cement, 50% relative humidity and an ambient temperature of 5℃, while varying the aggregate types. For all the aggregate types the maximum net shortening occurs at the 15th floor level with values of 163.8 mm, 178.9 mm, 187.8 mm and 208.8 mm for Basalt, Quartzite, Limestone and Sandstone respectively. Basalt produced the least net shortening with the Quartzite, Limestone and Sandstone aggregate giving net shortening values that are 9%, 15% and 27% greater than that of Basalt.

The results obtained with ambient temperature of 30℃, 50% relative humidity and normal hardening cement while varying the types aggregate used are shown in Fig. 12. Similar behaviour was observed with the change in ambient temperature from 5℃ to 30℃. For all the aggregate type, the maximum net shortening occurs at the 15th floor level with values of 151.6 mm, 166.3 mm, 175.0 mm and 196.1 mm for Basalt, Quartzite, Limestone and Sandstone respectively. Basalt again produced the least net shortening with Quartzite, Limestone and Sandstone aggregate giving net shortening values that are 10%, 15% and 29% greater than that of Basalt.

Table 6 Results summary for the effect of aggregate type on column shortening

50% RH-N Type Cement	Basalt	Quartzite	Limestone	Sandstone	Δ(max-min) Difference(mm)	Δ (max-min) (%)
Shortening at 15th Floor at 5°C Ambient Temperature	163.8	178.9	187.8	208.8	45.0	27
Shortening at 15th Floor at 30°C Ambient Temperature	151.6	166.4	175.0	196.1	44.5	29

As far as aggregate mineralogy is concerned, Basalt gives the best results in this simulation, that is, the least net shortening effect. It is followed by Quartzite, Limestone and finally Sandstone which gives the highest values of shortening. The effect that various aggregate types have on net shortening can be attributed to their mineral composition which impacts their moisture related shrinkage properties. As aggregate with high moisture absorption rate can result in higher shrinkage in hardening concrete.

The mineralogical origin of the aggregates used in the concrete mixtures has thus a significant impact on the post-casting deformations of concrete and thereby on the shortening of the concrete columns.

Table 6 shows the results summary of the investigation on the effect of aggregate mineralogy on the total net shortening of the columns in a 24-storey building. Changing the type of aggregate used can alter the shortening by between (27%-29%) for ambient temperatures of 5°C and 30°C respectively.

5. Conclusions

This study evaluated column shortening in mid-rise concrete structures, with focus on the effects of ambient temperature, relative humidity, cement hardening speed and aggregate type. The study approach used the The Concrete Centre model for column shortening prediction produced insightful results.

The results show that the effect of the temperature on the total net shortening of columns can be considered as negligible compared to that of the other factors considered. Nonetheless, to reduce the shortening of the columns in a given project, consideration should be given to the erection of the structure in warmer weather when possible.

Furthermore, this study indicates that the total net shortening of columns can be reduced by 20% to 10% in 12-and 24-storey buildings by increasing the relative humidity from 50% to 80%. Additionally, cement hardening speed can be considered as insignificant for buildings up to 24-storey. However, in the case of a 12-storey building, the effect of cement type on total net column shortening becomes substantial.

Finally, the results also indicate that the aggregate type used when compared with the other factors considered has the most substantial impact on column shortening. Changing the aggregate type can alter the shortening by 27% with an ambient temperature of 5°C and 29% with an ambient temperature of 30°C.

The results of this study show that environmental factors that are the least controllable have less significant impact on column shortening. Column shortening can be significantly reduced by modifying controllable parameters such as the aggregate and cement types.

6. Recommendation

From the conclusion above, it can be recommended that using Limestone and Sandstone as aggregate in buildings over 13 storeys should be avoided. Furthermore, Basalt should be preferred to Quartzite when possible. Generally, it can be said that igneous rocks should be considered as first choice aggregate for high-rise concrete buildings, followed by metamorphic rocks.

Use of sedimentary rocks as aggregate should be discouraged even for low-rise buildings. This is that even though the shortening of the columns is not usually an issue in low rise buildings, creep and shrinkage deformations are concerns in terms of concrete cracking. Sedimentary rocks give the highest values of creep and shrinkage deformations. Moreover, aggregates with higher moduli of elasticity produce smaller relative values of column shortening.

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