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Deformations of Composite Precast Concrete Slabs Subject to Creep and Shrinkage

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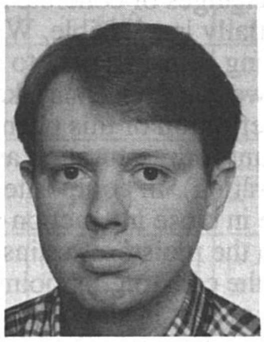


Mika Lydman, born 1964, received his Master of Science degree from Helsinki University of Technology in 1991. In 1993 he became a researcher at the Laboratory of Structural Engineering in HUT. His main research interests concern composite and concrete structures.

Summary

The time-dependent response of composite concrete slabs made of precast floor plate and cast in situ concrete are analytically and experimentally studied. Analysis is carried out with an algebraic age-adjusted effective modulus method and a relaxation procedure. The moisture transport between concrete components of different ages has been taken into account. Long-term test results on five statically determinate composite slabs are reported. The agreement between test results and theory is shown to be good.

1. Introduction

Composite flooring systems are widespread in building construction. Their scope of use covers cast in-place monolithic slabs, e.g. floor and roof systems for buildings, parking garages and bridge decks. Composite concrete slab consists of precast concrete floor plates and cast in situ concrete topping. The floor plate is used as permanent formwork for the cast in-place topping with which it works structurally after hardening of the in situ concrete and finally forms the composite concrete structure. These kinds of composite structures are very highly sensitive to creep and shrinkage properties of concrete. In practice it has also been found that in some cases the long-term deflections of composite concrete slabs have not been predicted with sufficient accuracy. In this paper, time-dependent deflections of composite concrete slabs under service loads are analytically and experimentally studied. Analysis is carried out on the basis of bending theory with plane cross sections, taking into account creep and shrinkage of concrete and relaxation of prestressed steel. The amount of prestressing is designed to be sufficient to avoid cracking of the concrete. The effects of creep and shrinkage are qualified by the age-adjusted effective modulus method and a relaxation procedure. Eurocode 2 [1] and RILEM model B3 [2] are considered when evaluating the magnitude of creep and shrinkage of concrete.

2. Theoretical model

When a composite concrete slab is subjected to load, its response is both instantaneous and time-dependent. Under a sustained load, the stress and strain in a prestressed concrete structure are subject to change for a long period of time. In this analysis, the creep analysis is simplified by applying a linear algebraic method called the age-adjusted effective modulus method (AEMM) and for stresses occurring at different ages, the principle of superposition is assumed. The total strain of uniaxially loaded concrete may be subdivided as

$$\varepsilon(t,t_0) = \varepsilon_e(t_0) + \varepsilon_c(t,t_0) + \varepsilon_{sh}(t,t_0) + \varepsilon_T(t) \quad (1)$$

in which $\varepsilon_e(t)$ is the instantaneous strain, $\varepsilon_c(t,t_0)$ is the creep strain, $\varepsilon_{sh}(t,t_0)$ is the shrinkage strain and $\varepsilon_T(t)$ is the thermal strain. Shrinkage is generally taken to mean drying shrinkage, which is the observed strain associated with the moisture diffusion out of concrete under drying conditions. In this research a linear relationship between the change in average longitudinal moisture strain and the average moisture changes of concrete has been assumed for the calculations. Drying shrinkage is also partially irreversible. When concrete is resaturated, swelling of concrete occurs, but the swelling is insufficient to completely compensate for the shrinkage that occurred on drying. Thus, we can divide shrinkage into reversible and irrecoverable components, but a unique definition of this phenomenon does not exist. Therefore, the analysis used generally does not account for resaturation and swelling of concrete during environmental changes (theory, no resaturation). In composite concrete slabs, the surfaces of the concrete components of different ages are in close interaction among themselves. Therefore the transition of the moisture and its effect on the moisture strains of the structure must be taken into account. The moisture transport between the construction joint surface retards the drying of precast concrete and speeds up the drying of cast in situ concrete. In this study this has been taken into consideration by a simplified calculation method (theory including resaturation) in which a part of the construction joint surface is assumed to be moisture permeable when evaluating the time function of shrinkage of precast and cast in situ concrete. Furthermore, for a time period after casting negative shrinkage strain for precast concrete has assumed. The evaluation of the length of the time period is done by means of diffusion theory.

If the concrete stress $\sigma_c(t_0)$ is applied at time t_0 and remains constant for time period t_0 to t, the load-dependent strain $\varepsilon_\sigma(t,t_0)$ at time t may be expressed as the sum of instantaneous component $\varepsilon_e(t_0)$ and creep component $\varepsilon_c(t,t_0)$. Creep coefficient $\phi(t,t_0)$ is defined as the ratio of creep strain $\varepsilon_c(t,t_0)$ at time t to the instantaneous elastic strain $\varepsilon_e(t_0)$ at time t_0. A stress introduced gradually at time period t_0 to t produces creep of smaller magnitude compared to a stress of the same magnitude applied at age t_0 and sustained during the period t_0 to t. Thus, the stress increment $\Delta\sigma_c(t)$ is treated as if it were introduced with its full magnitude at age t_0 and sustained to age t but the creep coefficient $\phi(t,t_0)$ is replaced by a reduced value which equals $\chi(t,t_0)\phi(t,t_0)$, where $\chi(t,t_0)$ is a parameter called the aging coefficient [3]. Use of the aging coefficient χ simplifies the analysis of strain caused by a gradually introduced stress increment $\Delta\sigma_c$. The total strain of concrete due to the applied stress is given by

$$\varepsilon_\sigma(t,t_0) = \varepsilon_e(t_0) + \varepsilon_c(t,t_0) = \sigma_c(t_0)\frac{1+\phi(t,t_0)}{E_c(t_0)} + \Delta\sigma_c(t)\frac{1+\chi(t,t_0)\phi(t,t_0)}{E_c(t_0)} \quad (2)$$

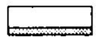
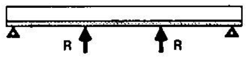
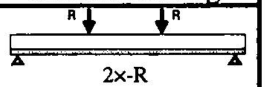
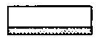
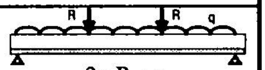
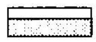
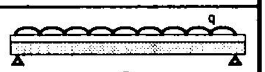
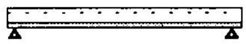
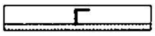
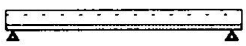
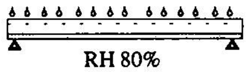
The first term in Eq. (2) represents the strain in concrete at age t due to a stress $\sigma_c(t_0)$ introduced at age t_0 and sustained during the period t_0 to t, and the second term the strain at age t due to a stress increment of magnitude zero at t_0 increasing gradually to a final value $\Delta\sigma_c(t)$ at age t.

3. Comparison of experimental and theoretical results

3.1 Test specimens and arrangements

Test results on five statically determinate composite slabs are reported for a time period of 434 days [4]. The composite slabs were composed of two main components, precast floor plates and cast in situ concrete. Three different types of precast prestressed concrete floor plates were tested: floor plates with a depth of 70 mm (FP70) and 140 mm (FP140), and floor plates with a depth of 70 mm stiffened by cold formed steel section (FPS70), which requires no propping during construction with spans up to 10 000 mm. The total slab depth in all specimens was 220 mm. The cross-sections of the specimens also include an amount of prestressed steel wires Ø5 equivalent to 36 wires at the width of 1200 mm. The initial prestress applied was 1320 MPa. In addition to prestressing steel, specimen type FPS70 also includes a cold formed L-type steel section as a stiffener of floor plates, which corresponds to the steel area of 2080 mm^2 (t=8 mm, equal to 20-180 of reinforcing bars). The floor plates were manufactured at a precast plant and they (and companion concrete specimens) were heat-cured after casting (T=50°C) 15 hours.

Table 1. Types of specimens and their loading history

Specimen	h_{tot}×b [mm]	Wires [units]	Cross-section	During casting in situ concrete	Long term external loading
FP 70/1	220×600 FP 70 mm	18	 600		 2×-R
FP 70/2	220×600 FP 70 mm	18	 600		 2×-R + q
FP 140	220×600 FP 140 mm	18	 600		 q
FPS 70/1 + stiffener	220×1200 FP 70 mm	36	 1200		
FPS 70/2 + stiffener	220×1200 FP 70 mm	36	 1200		 RH 80%

After manufacturing the composite slabs were simply supported on supports at a spacing of 7200 mm. Specimens FP70/2 and FP140 were loaded with an external sustained uniformly distributed load q of 5.4 kN/m^2 applied by concrete weights, specimens FP70/1 and FP70/2 were propped during casting in situ concrete and therefore they also had support forces 2×-R as long-term loads. Specimens FPS70/1 and FPS70/2 were subjected to selfweight only. The sides of all specimens were covered by a waterproofing layer to ensure that drying rate of concrete (and notional size) is similar to infinite slab structures. The slab specimens were stored at an average temperature 19 °C and average value of relative humidity 50%. In addition to this, specimen FPS70/2 was air-cured at an elevated relative humidity of 80%, which equals out of doors atmospheric conditions according to EC2 [1]. The last measurements considered in this paper were made 434 days after manufacturing the floor plates. The deflection curves of the slabs were measured at ten different points along the span of the slabs at regular intervals.

Table 2. The testing procedure of the specimens

t, day	Main events of testing procedure
0	Casting of precast floor plates (concrete type HC and HCP)
1	Transfer of prestressing (beginning of shrinkage of panels)
14	Casting of in situ concrete (concrete type NC)
19	Curing of concrete terminated (beginning of shrinkage of in situ concrete NC)
20	The removal of temporary supports (applying support forces -R)
21	First measurements of deflections and strains
33	Start of loading of specimens (applying an external load q)
37	Raising of the relative humidity of specimen FPS70/2

3.2 Experimental and theoretical material properties

During casting of the slab specimen, companion concrete specimens were taken for material property tests [4]. Concrete types tested were type HC (heat cured), type HCP (heat cured with plasticizer) and type NC (normal concrete), which were used, respectively, for precast floor plate of specimen FP70/1, FP70/2 and FP140, for precast floor plate of specimen FPS/1 and FPS/2 and for the cast in situ part of all specimens. Nine concrete cylinder shrinkage specimens (Ø×L 100×200 mm) were cast, and the strains were measured over a period of 2¼ to 636 days. The specimens were stored during measurements at a constant temperature of 20°C and a RH of 45%. Nine concrete cylinders (Ø×L 100×200 mm) were placed inside a creep testing frame and total strains were measured when specimens were loaded with a sustained stress of 30% of their compressive strength. The specimens were loaded after 2¼ days and 28 days. In Figs. 1 to 6 are presented measured and calculated compliance functions (i.e. strain caused by a unit uniaxial constant stress given in 10^{-3} MPa^{-1}) and shrinkage strains of concrete types HC and NC.

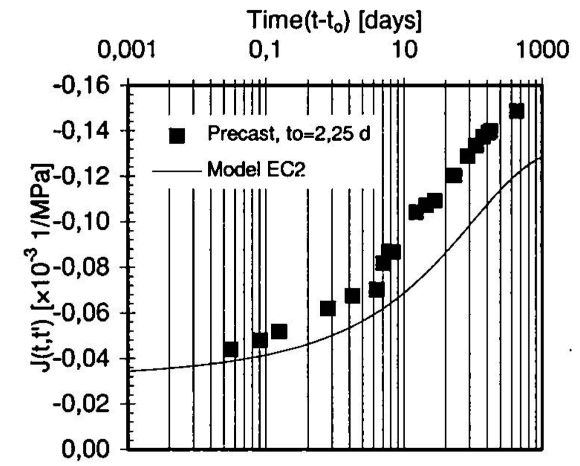


Fig. 1: Measured and calc.compliance function of precast concrete (type HC, t_0 = 2¼ d)

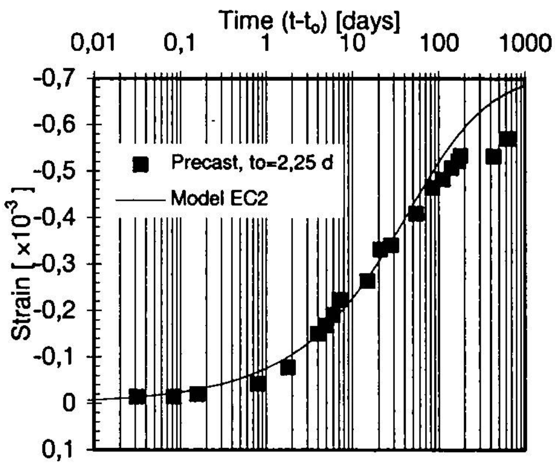


Fig. 2: Measured and calc. shrinkage strain of of precast concrete (type HC, t_0 = 2¼ d)

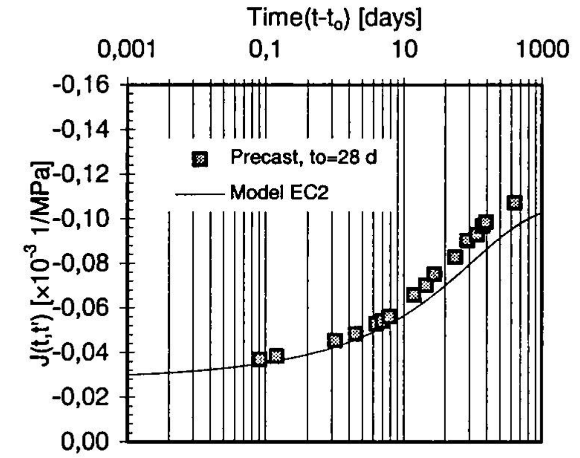


Fig. 3: Measured and calc.compliance function of precast concrete (type HC, t_0 = 28 d)

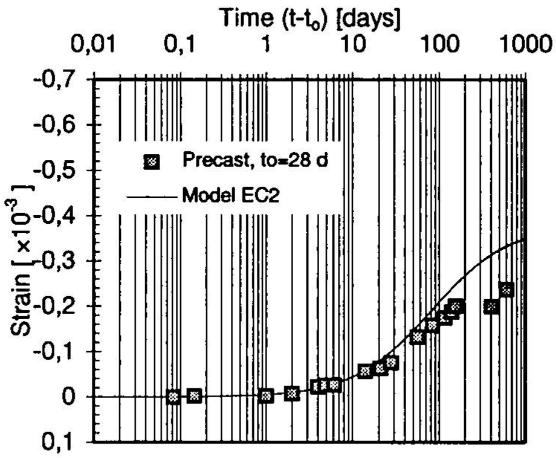


Fig. 4: Measured and calc. shrinkage strain of of precast concrete (type HC, t_0 = 28 d)

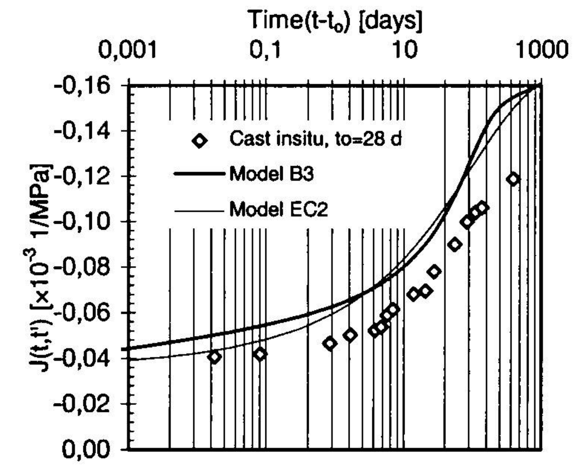


Fig. 5: Measured and calc.compliance function of cast in situ concrete (NC, t_0=28 d)

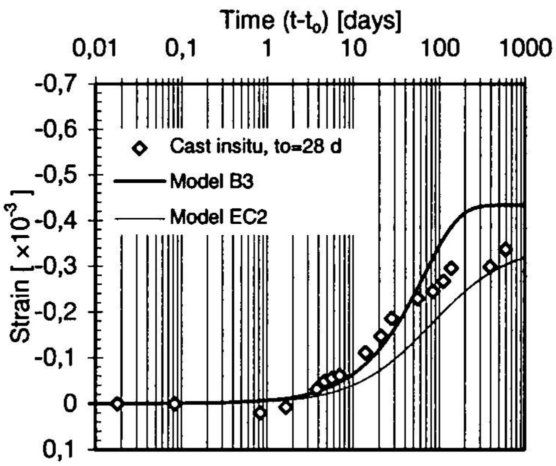


Fig. 6: Measured and calc. shrinkage strain of of cast in situ concrete (NC, t_0 = 28 d)

From Figs. 1 to 6 it can be seen that the differences between measured and calculated values of compliance functions and shrinkage strains are within the acceptable limits compared to mean coefficient of variation of the predicted values reported elsewhere [1, 2]. The differences between measured and calculated values of compliance function varied in the range of -18.7% to +30.4% and for shrinkage strain in the range of -10.1% to +28.8%.

Four concrete cylinders of each concrete type and testing age were tested to obtain their elastic modulus and cylinder compressive strength development with time. In addition to these, three cylinders of concrete types HC and NC were tested to determine their splitting tensile strength. The mean value of the compressive cylinder strength f_{cm} and the secant elastic modulus E_{cm} at an age of 28 days were, respectively, 46.5 MPa and 35500 MPa for concrete type HC, 40.4 MPa and 29500 MPa for concrete type HCP and 29.2 MPa and 27700 MPa for concrete type NC. The mean splitting tensile strength was 3.4 MPa for HC concrete and 2.3 MPa for NC concrete.

3.3 Experimental and theoretical results of deflections

The midspan deflections measured at various times are shown in Figs. 7 to 10 for each specimen. The solid lines represent the results from the theory including the moisture transport between the concrete components of different ages. For comparison, the results of a calculation are shown in which all assumptions are the same except that the construction joint surface is assumed not to be moisture permeable at all, see the dashed lines. The values do not present the absolute values of deflection curves but the change of deflection from the time moment of t = 21 days. Deflections are positive when downwards and the reference points in relation to measured deflections were 100 mm from the support of every specimen.

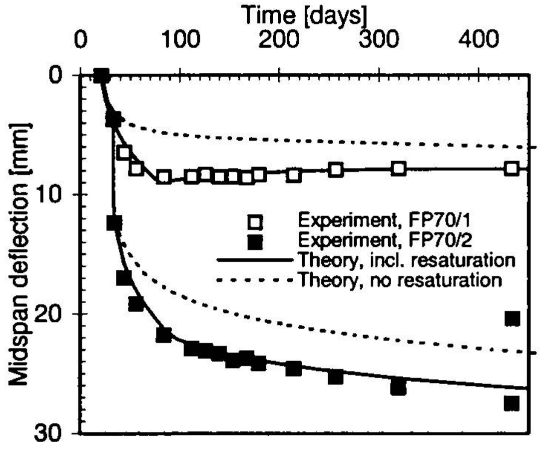


Fig. 7: The change of midspan deflection of specimens FP70/1 (□) and FP70/2 (■)

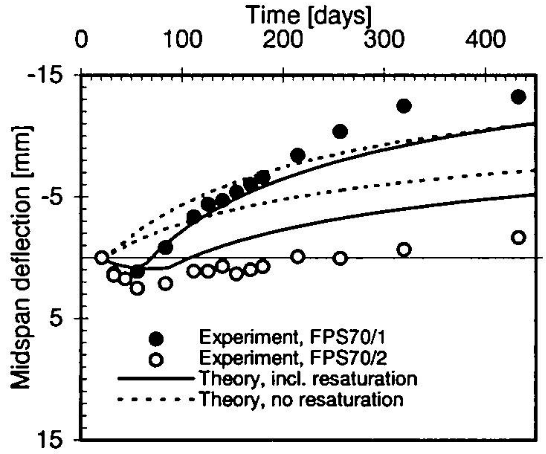


Fig. 8: The change of midspan deflection of spec. FPS70/1(●) and FPS70/2 (○)

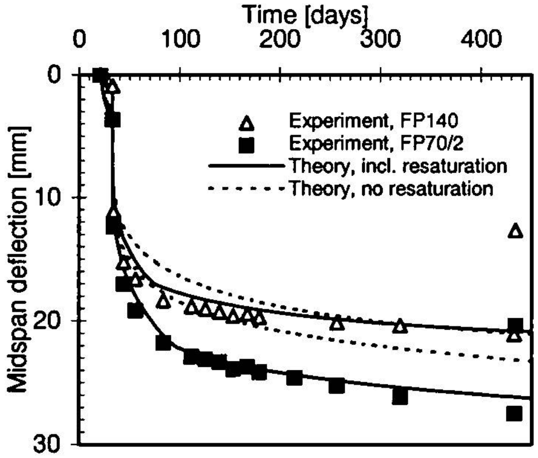


Fig. 9: The change of midspan deflection of specimens FP140 (Δ) and FP70/2 (■)

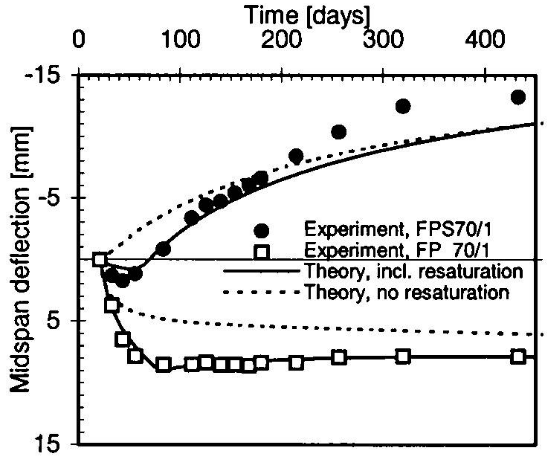


Fig. 10: The change of midspan deflection of spec. FP70/1 (□) and FPS70/1 (●)

Fig. 7 shows the change of midspan deflections of specimens FP70/1 and FP70/2. The deflections at the end of tests were downwards for both specimens despite prestressing (for FP70/1 and FP70/2 +7.84 mm and +27.48 mm, respectively). From the figure the effect of the long-term external load q on the deflections of composite concrete slabs can be seen. The permanent deflections increased about 160% and with instantaneous deflections, the increase was over 250% in the case of long-term loading. The change of midspan deflections of specimens FPS70/1 and FPS70/2 is presented in Fig. 8. From Fig. 8 one can see that the deflections were first downwards but from the time moment of about 50 to 70 days upwards for both specimens due to the prestressing and the influence of non-prestressed steel (for FPS70/1 and FPS70/2 -13.21 mm and -1.65 mm respectively). Moreover, the elevation of relative humidity from 50% to 80% reduced powerfully (+11.56 mm) the upward deflections. Fig. 9 shows the change of midspan deflection of specimen FP140 including unloading at t = 434 days. Comparison with specimen FP70/2 is also made. From Fig. 9 one can see the influence of the construction method (propped compared to non-propped construction) on long-term deformations (for FP140 and FP70/2 +21.09 mm and +27.08 mm respectively). In both specimens the cross sections of composite slabs are very similar, but the support forces R caused by propping during casting the in situ concrete, increase the total deflections of the structure of about 30% and permanent deflections of 61%. In Fig. 10 is compared the change of deflections of specimens FP70/1 and FPS70/1, which had no external loading. From Fig. 10 the influence of construction method on the deformations can also be seen. Reversed support forces R increase the deflections downwards and the total difference was 21.05 mm between the specimens.

4. Discussion and conclusions

The structural effects of creep and shrinkage in composite prestressed concrete slabs were investigated both experimentally and analytically. Time-dependent deformations were measured in five slab specimens and shrinkage and creep strains were measured in the companion specimens. The experimental measurements were compared with theoretical results for deflection calculations. The companion tests showed that the differences between measured and calculated creep and shrinkage strains varied in the range of -19% to + 30%. The magnitude of the variation is about the same as reported elsewhere [1, 2].

The flexural tests showed that the effect of creep and shrinkage dominates the long-term behaviour of one-way spanning concrete composite slab. The permanent midspan deflections of composite slabs increased 160% and in the case of total deflections (permanent and instantaneous) the increase was over 250% in the case of sustained uniform load of 5.4 kN/m^2. It was also shown that the influence of the construction method (i.e. the loading history of the structure) on long-term deformations is significant. The support forces caused by propping during casting the in situ concrete increased the total deflections of the composite slab by about 30%. Moreover the elevation of the ambient relative humidity from 50% to 80% prevented almost totally the development of long-term deflections.

It is also shown that the theory including the moisture transport between the concrete components of different ages has a good agreement with experimental results in the case of uncracked composite concrete slabs. If the moisture transport between the concrete components is omitted from the theory, the accuracy of the obtained results decreases distinctly. Therefore, in composite concrete structures the moisture transport between the concrete components of different ages must be taken into account in order to get theoretical results with good accuracy.

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