A CREATIVE VALIDATION METHOD FOR SELF COMPACTING CONCRETE (SCC) LATERAL PRESSURE MODEL USING ARCHIMEDES' LAW

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ABSTRACT: There is currently no standard that can be used to design formworks capable of predicting lateral pressure applied by Self Compacting Concrete (SCC). Formwork designers have been suggested to design formwork to withstand full hydrostatic lateral pressures unless another rational method based on appropriate and reliable experimental studies is presented. This generally obliges contractors to design very strong formwork systems, with additional and unnecessary costs. On the other hand, approximately all previous studies focused on maximum lateral pressure of SCC and its variation over the formwork height is almost non-existent. In this study, thirty experimental tests were carried out on six series of tubular PVC formworks with the same height of 1500 mm and internal diameters of 70 mm, 100 mm, 120 mm, 130 mm, 170 mm and 240 mm, respectively. In this regard, the total volumetric deformations of formworks are investigated. Simultaneously, the theoretical magnitudes of these deformations are calculated by Finite Element (FE) analysis under the hydrostatic assumption. The results show the total real deformations of formworks have a good agreement with numerical values under hydrostatic pressure assumption when the diameter of formwork increases.

Keywords: Archimedes' Law, Self Compacting Concrete (SCC), Lateral pressure, Formwork, Hydrostatic

1. INTRODUCTION

Lateral pressure applied on formwork systems by self-compacting concrete (SCC) has a significant role in the design of the formwork systems and is one of the hurdles for using SCC in the cast in place projects. Several factors including, placement method, material properties and, formwork characteristics affect the formwork maximum lateral pressure. Therefore, approximately all previous studies focused on maximum lateral pressure of SCC and its variation over the formwork height are non-existent.

In this study, experimentally measured volumetric deformations of several SCC filled tubular PVC formworks and their corresponding numerically estimated values using the Finite Element method are compared. Finally, the validity of hydrostatic behavior assumption of the lateral pressure of SCC is evaluated.

2. LITERATURE REVIEW

The literature has repeatedly shown that SCC lateral pressures far lower than hydrostatic pressure can be obtained, but still a widespread concern of accommodating high pressures exist. In this regard, several models for predicting the lateral pressure during concrete casting have been developed. For

example, Billberg et al. [1] studied casting pressure of eight instrumented wall elements with various geometries using different SCC mix designs as well as various casting rates. Results showed a wide range of form pressures, and the evaluation of models considered revealed that they were all capable of predicting the lateral form pressure satisfactorily. Omran et al. [2] as part of two similar studies presented the influence of formwork width, shape and surface material as well as concrete temperature, casting depth, placement rate, waiting period between successive lifts and concrete thixotropy on lateral pressure characteristics. The results revealed that the increase in formwork width could increase the lateral pressure and delay the formwork removal time. The formwork surface materials did show a notable effect on formwork pressure, and different pressure decay responses were observed for each formwork material. In the experimental study by Tuyan et al. [3] the influence of thixotropy determined by different test methods on the formwork pressure of SCC with different compositions were investigated. They determined the effect of water/binder (w/b) ratio, slump flow diameter and coarse aggregate/total aggregate ratio on thixotropy and formwork pressure of SCC. A serious correlation between thixotropy and formwork pressure was found in SCC mixtures having low w/b ratio. There was a strong

relationship between thixotropy and formwork pressure in low slump flow SCC mixtures, while thixotropy revealed a good correlation with the formwork pressure in high slump flow SCC mixtures. Then, new models were developed to predict the formwork pressure of all types of mixtures as a function of thixotropy and time. Also, a parametric study was employed to evaluate the effect of concrete consistency level, coarse aggregate content, sand-to-total aggregate ratio, paste volume, and nominal maximum size of aggregate on SCC thixotropy and formwork pressure by Omran et al. [4]. The investigation resulted in proposing statistical models to determine the effect of each of the modeled mixture parameters and their interaction with lateral pressure. Contour diagrams were established to compare the trade-off between the effects of the different mixture parameters on thixotropy and formwork pressure characteristics. Due to the increasing structural use of recycled materials [5-8], Matar et al. [9] reported some experimental data obtained from 21 SCC mixtures cast in 200 mm × 400 mm × 1600 mm formwork containing up to 4.71% vertical steel. Tests revealed that mixtures incorporating RCA exhibited decreased initial pressure, which was mostly attributed to higher aggregate surface roughness increasing internal friction. The reduction in pressure was notable with the increase in vertical steel density, suggesting that the reinforcement cage confines the plastic concrete and bears part of its load. Assaad et al. [10] reported experimental data obtained from 32 SCC mixtures possessing different stability levels and cast in 1.6 m high formwork containing various combinations of vertical and transverse steel bars. Results showed that mixtures incorporating recycled aggregates exhibited decreased maximum pressure, given the higher RCA surface roughness that promotes internal friction and material build-up at rest. The transverse steel was around 1.5 times more influential than vertical steel in reducing the formwork pressure. Also, the rates of pressure drop over time were not altered because of steel, implying that pressure decay is governed by concrete properties such as thixotropy, RCA friction, and cement hydration. In addition, the effect of density of vertical reinforcement and spacing between reinforcing steel and formwork surface on SCC lateral pressure are investigated by Omran et al. [11] using laboratory-scale columns measuring 1.4 m in height. The effects of casting rate and concrete structural build-up at rest were also considered. The results showed that the increase in steel reinforcement density placed at the relatively small cover of 25 mm could reduce the maximum lateral pressure. The lateral pressure reduction is less significant when the concrete cover increases to 50 mm. Further, to study the SCC

lateral pressure, a field test method and model is presented by Henschen et al. [12]. Their study predicts the formwork pressure using a calibrated behavior. The simple formwork pressure model is shown to agree well with experimentally measured values during the construction of two tall-walls, suggesting that this method and model can contribute to the increased cost efficiency of SCC construction while maintaining safe practices. Khayat et al. [13] presented the results of two campaigns of field validation carried out at Quebec and Illinois to validate the prediction models. The results confirmed that the established models offer an adequate prediction of form pressure exerted by SCC. In addition, Labuschagne [14] presented the results of an experimental investigation undertaken using on-site conditions, aimed at studying the influence of placement methods, various casting rates, as well as implementing predetermined waiting periods between castings. The influence of each of these parameters was evaluated by using six vertical instrumented wall elements. The test results showed that with high casting rates from the top of the formwork system, hydrostatic pressure could be expected. It is shown that by interrupting the casting procedure and implementing waiting periods to allow the fresh SCC to set, decreases the lateral pressure exerted. It was shown that, when pumping from the base of the formwork system, hydrostatic pressure could be expected during the casting process and that lateral pressures above the hydrostatic pressure could be expected during the casting of the SCC. Saleem et al. [15] proposed a new FEM based model for simulating the evolution of formwork pressure exerted by fresh SCC. The introduced model considers self-compacting concrete as an isotropic linear elastic homogeneous material confined in a rigid body, with the boundary layer behavior being simulated as viscoplastic. The amounts of the boundary shearing stress at wall vary with height depending on the interrupting time between the pouring of a specific portion of the SCC to the moment the pressure measurement is taken. Experimental tests were conducted on a full-scale formwork to determine the evolution of formwork pressure exerted by SCC mixes made with different mineral materials. The experimentally obtained pressure-time assessment curves correlated absolutely well with those obtained from the numerical model. The results indicated that the decay of formwork pressure after an initial period becomes depended to the Poisson ratio of the mixed concretes.

3. MATERIAL AND METHODS

The American Society for Testing and Materials (ASTM) procedures are followed for determining the properties of the concrete components in this

study.

3.1 SCC

In this study, a self-compacting concrete with a 28-day compressive strength of about 40 MPa is used as filling material. The specification of constituent materials are as follows:
• Cement: Ordinary Portland Cement (OPC)
• Fly ash: Grey, Class F, based on ASTM C618
•Admixtures: Polycarboxylic ether based superplasticizer (ASTM C494 type F)
• Fine aggregates: Natural sand with a maximum size of 4.75 mm, bulk density = 1,810 kg/m^3
•Coarse aggregates: Crushed stone with a maximum size of 16 mm, bulk density = 1,550 kg/m^3

3.2 PVC Formwork

• Young's modulus: 2,900 MPa
• Poisson ratio: 0.4

3.3 Concrete Mix Design and Properties

In this study, the following SCC mix design using the mentioned materials is used. Further, the results of workability tests are as follows:

• Coarse aggregate: 760 kg/m^3
• Fine aggregate: 910 kg/m^3
• Cement: 400 kg/m^3
• Water/Powder ratio: 0.3
• Water/Cement ratio: 0.4
• Water: 160 kg/m^3
• Fly ash: 80 kg/m^3
• Superplasticizer: 2% (percent of cement)
• L Box test: H2/H1 = 0.83
• U Box test: H1 – H2 = 25 mm

4. NUMERICAL INVESTIGATION

In this study, six series of Finite Element (FE) analyses were carried out on numerical models using ANSYS R15. These numerical simulations were carried out to determine the linear and volumetric deformation of six types of SCC filled tubular PVC formworks (S1 to S6). The lengths of these formworks are the same as 1500 mm. The internal diameters of them are 70 mm, 100 mm, 120 mm, 130 mm, 170 mm and 240 mm (Figure 1). Therefore, the internal diameters to length ratios of S1 to S6 are 0.05, 0.07, 0.08, 0.09, 0.11 and 0.16 respectively. Further, the thickness of the PVC formworks is 2 mm.

The total volumetric deformation of each formwork is calculated under hydrostatic behavior assumption.

Fig1. Studied PVC formworks (S1 to S6).

Figures 2 to 4 show the lateral deformation of formworks S1 to S6, respectively.
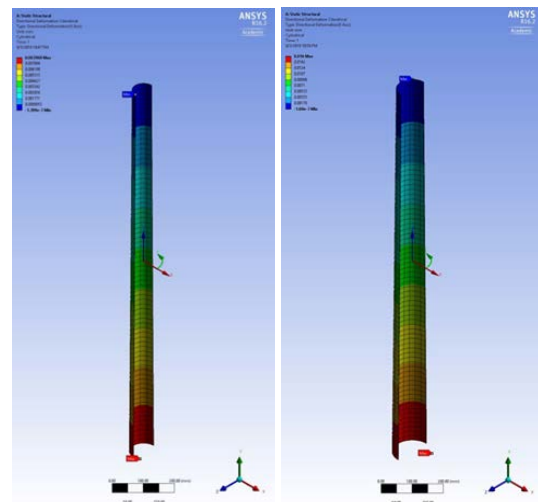

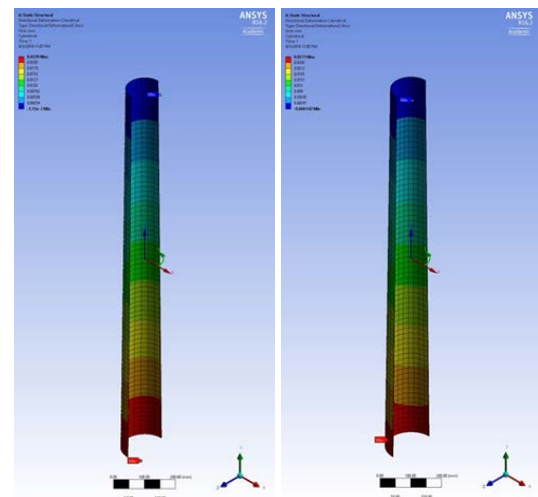Fig2. The lateral deformation of S1 (left) and S2 (right).

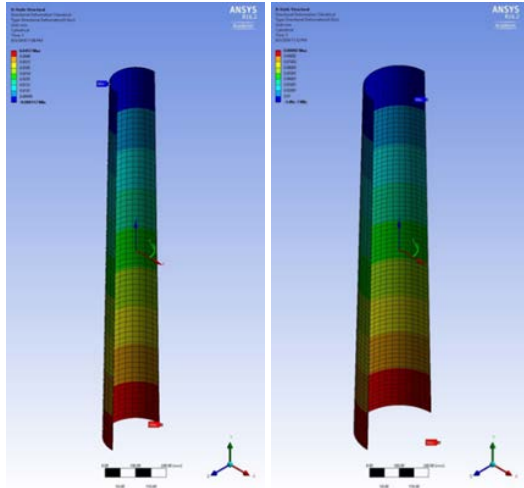Fig3. The lateral deformation of S3 (left) and S4 (right).

Fig4. The lateral deformation of S5 (left) and S6 (right).

As can be seen in Figures 5 to 7 the equations of linear deformation of PVC formworks under SCC lateral pressure are as follows:

- $y = 5E\text{-}6x + 35$,
- $y = 1E\text{-}5x + 50$,
- $y = 2E\text{-}5x + 60$,
- $y = 5E\text{-}5x + 65$,
- $y = 3E\text{-}5x + 85$,
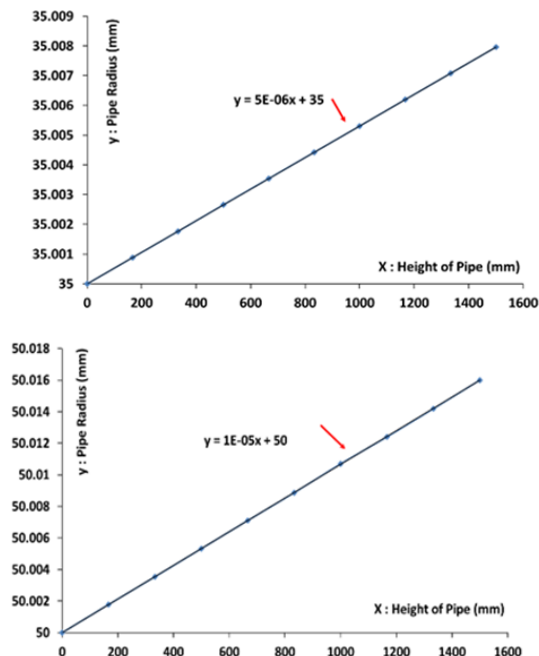- $y = 6E\text{-}5x + 120$

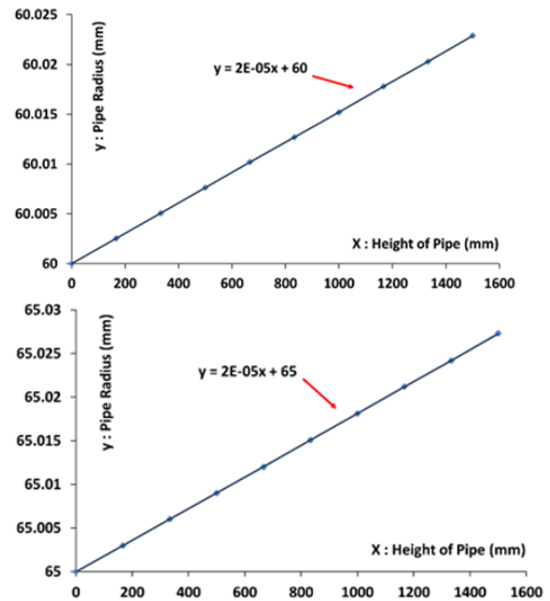Fig5. Equations of lateral deformation of S1 (up) and S2 (down).

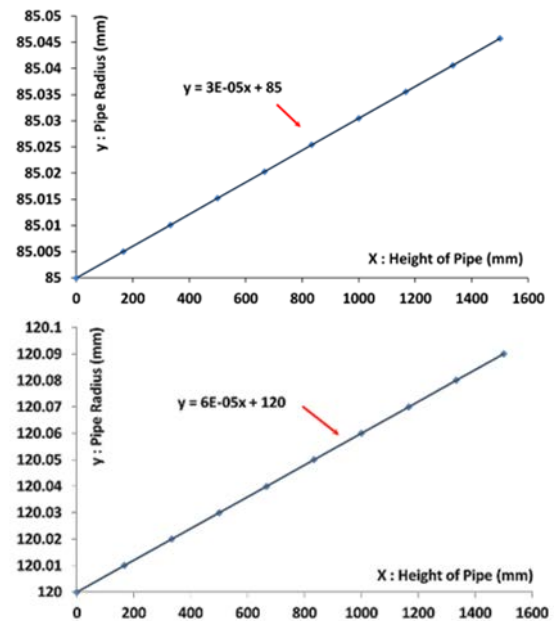Fig6. Equations of lateral deformation of S3 (up) and S4 (down).

Fig7. Equations of lateral deformation of S5 (up) and S6 (down).

Regarding these equations, the secondary numerical internal volumes of specimens S1 to S6 are calculated as 5,774,000 mm^3, 11,780,000 mm^3, 16,970,000 mm^3, 19,920,000 mm^3, 34,070,000 mm^3 and 67,910,000 mm^3, respectively. These volumes are comparable with their primary internal volumes of 5,769,750 mm^3, 11,775,000 mm^3, 16,956,000 mm^3, 19,899,750 mm^3, 34,029,750 mm^3 and 67,824,000 mm^3. Figure 8 shows variation of the volumetric deformation of PVC formworks vs its diameter.
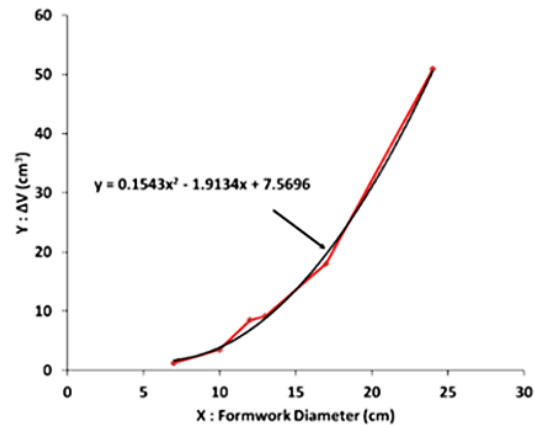
Fig8. Variation of the volumes of PVC formworks vs their diameters.

5. NUMERICAL INVESTIGATION

In order to compare the numerical results with real volumetric deformation of samples, two series of experimental tests were conducted. The purpose of these experiments was to determine the actual secondary volumes of specimens. The difference between numerical results and experimental results can indicate the degree of accuracy of the hydrostatic assumption.

5.1 First series of experimental tests, density method

In this series of experimental tests, using 100 mm * 100 mm *100 mm cubic steel molds, the density of five control cubic concrete specimens was calculated (Table 1). Also, thirty cylindrical PVC formworks (five formworks @ six types) are filled with SCC (Figure 9).

Table1   Density of hardened SCC

Specimen	Nominal Volume (m^3)	Measured Weight (kg)	Calculated Density (kg/m^3)
1	0.001	2.412	2412
2	0.001	2.42	2420
3	0.001	2.418	2418
4	0.001	2.395	2395
5	0.001	2.415	2415
Average			2412

Fig9. Types of SCC filled PVC formworks (S1-S6)

Subsequently, after drying the concrete, the

samples were removed from the molds. Then using a digital scale and measured density of concrete (Table 1), the volume of each specimen was calculated. Results are summarized in Table 2.

Table2. Secondary volumes of specimens in series 1 of experimental tests.

Specimens	Density (kg/m^3)	Measured Weight (kg)	Average Measured Weight (kg)	Secondary Experimental Volume (mm^3)
S1		13.86		
S1		13.925		
S1		13.75		
S1		14.085		
S1		13.975		
S1	2412		13.92	5770850
S2		28.39		
S2		28.485		
S2		28.36		
S2		28.389		
S2		28.446		
S2	2412		28.4	11780200
S3		40.98		
S3		40.582		
S3		40.944		
S3		41.211		
S3		40.933		
S3	2412		40.93	16956980
S4		48.25		
S4		48.15		
S4		47.575		
S4		48.545		
S4		47.595		
S4	2412		48.023	19911750
S5		82.25		
S5		82.165		
S5		81.958		
S5		82.165		
S5		82.262		
S5	2412		82.16	34053750
S6		163.854		
S6		163.45		
S6		164.15		
S6		164.42		
S6		162.826		
S6	2412		163.74	67886700

5.2 Second series of experimental tests, Archimedes' method

In the second series of experimental tests, since nucleation and propagation of cracks are inevitable in the concrete surfaces [16,17] all concrete cylindrical specimens were waterproofed by a fragile layer of paraffin. Then, the weights of all waterproofed concrete cylinders were measured in water. According to Archimedes' law, the differences between in-air weights (Section 6.1) and in-water weights are equal to the weights of displaced water for each of the specimens. The volume of displaced water would be equal to the second amount of each formwork (Figures 10&11). The related calculations are seen in Table 3.
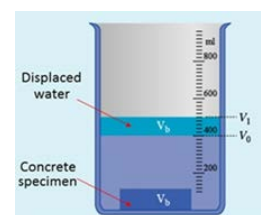

Fig10. Conceptual structure of the Archimedes' method.

Fig11. An in-water weight measurement of specimens (Test series 2).

Table3. Secondary volumes of specimens in the series 2 of experimental tests.

Specimen	Average In-air Measured Weight (kg)	Average In-water Measured Weight (kg)	Weight of Displaced Water (kg)	Volume of Displaced Water (mm³)	Secondary Experimental Volume Archimedes' Method (mm³)
S1	13.92	8.149	5.771	5771000	5771000
S2	28.4	16.626	11.774	11774000	11774000
S3	40.93	23.961	16.969	16969000	16969000
S4	48.023	28.113	19.91	19910000	19910000
S5	82.16	48.097	34.063	34063000	34063000
S6	163.74	95.854	67.886	67886000	67886000

5.3 The average amounts of the secondary volumes of specimens

Based on the results of two series of experimental tests, the average amounts of the secondary volumes of specimens are calculated in Table 4.

Table4. The average amounts of the secondary volumes of specimens.

Specimen	Secondary Experimental Volume – Density Method (mm³)	Secondary Experimental Archimedes' Method (mm³)	Average Secondary Experimental Volume (mm³)
S1	5770850	5771000	5770925
S2	11780200	11774000	11777100
S3	16956980	16969000	16962990
S4	19911750	19910000	19910875
S5	34053750	34063000	34058375
S6	67886700	67886000	67886350

6. CONCLUSION

The conservation factor of hydrostatic behavior assumption (the ratio of numerical volumetric deformation to experimental volumetric deformation) is calculated using the results of both of numerical investigation and experimental tests, for all of the formwork types. This factor is shown in Table 5 and Figure 12.
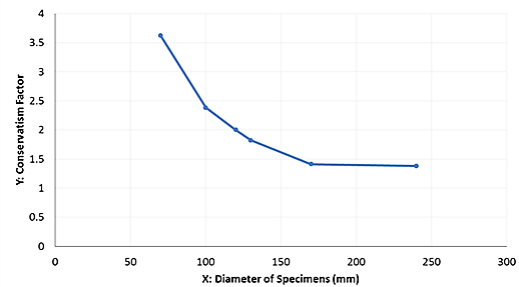

Fig12. Conservation factor VS the diameter of the cylindrical formworks.

Based on the results mentioned above we can draw the following conclusions:

- The conservatism factor increases with tubular formwork diameter reduction.
- The hydrostatic behavior assumption can apply at least 38 % overload on the tubular specimens with diameters less than 240 mm.
- The overload and consequently the over the cost of hydrostatic behavior assumption can reach to at least 262 % in narrow tubular formworks.
- The conservatism factor would have negligible variation when the diameter of the cylindrical formworks is greater than 170 mm.
- When SCC filled the cylindrical PVC formworks are designed using hydrostatic behaviour assumption, the equation of conservatism factor could be considered as:

$$y = -8E(-7) \; x^3 + 0.0005 \; x^2 - 0.1089 \; x + 8.9532 \quad (1)$$

Where:
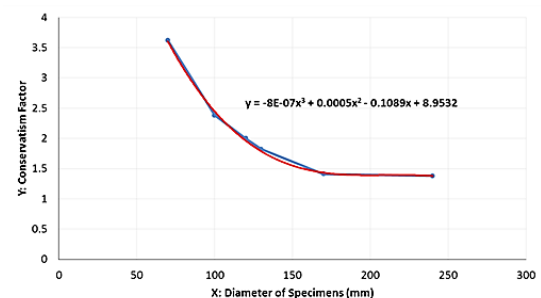x: the diameter of formwork (mm) (Figure 13)

Fig13. The equation of conservatism factor for SCC filled cylindrical PVC formworks.

Table 5. Conservation factor of hydrostatic assumption for all of the formwork types.

Specimen	Primary Volume (mm^3)	Secondary Numerical Volume (mm^3)	Average Secondary Experimental Volume (mm^3)	Numerical Volumetric Deformation (mm^3)	Experimental Volumetric Deformation (mm^3)	Conservatism Factor
S1	5769750	5774000	5770925	4250	1175	3.62
S2	11775000	11780000	11777100	5000	2100	2.38
S3	16956000	16970000	16962990	14000	6990	2.00
S4	19899750	19920000	19910875	20250	11125	1.82
S5	34029750	34070000	34058375	40250	28625	1.41
S6	67824000	67910000	67886350	86000	62350	1.38

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