Back Analysis of Self-Compacting Concrete Rheological Parameters Based on H-B Model

Shuai Zeng[1, a], Jianjun Shi[1,b], Wenqiang Guo[1,c]

[1] School of Urban Construction,The University of South China ,HengYang 421001,Hunan Province,China

[a]619667145@qq.com, [b] sjj6621@163.com, [c] 409956228qq.com

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Abstract. The rheological parameters of Fresh SCC were examined through the theory of rheology, the rheological model of Fresh SCC was assumed to be H-B rheological model, the flowing time $T_i^{'}$ of Fresh SCC in the simulated L-box through Fluent, later compared with the flowing time T_i of Fresh SCC in the actual L-box, the target function was established according to the least square method, three rheological parameters τ_0, k and n were optimized performing the pattern search method, and 6 sets of rheological parameters of τ_0, k and n acquired from the back analysis underwent the V-funnel verification test, which demonstrates the feasibility to back-analyze the H-B model rheological parameters to some extent.

1.Introduction

Self-compacting concrete (SCC) can fill the formwork to form the uniform compacting concrete only by gravity without the application of concrete vibrating. To date, many domestic and foreign scholars have applied the theory of rheology to examine the rheological parameters of fresh SCC. Yang Zhou [1]operated CFD to make the finite element normal analysis based on Binghan model, and back-analyzed the rheological parameter τ_0 and μ_p of fresh SCC, and demonstrated the feasibility to back-analyzed the rheological parameters. Jingqi Li[2] did the L-box simulation based on H-B rheological model, three parameters τ_0, k, n of the Herschel-Bulkley(H-B) model were experimentally measured, and the reliability of simulating SCC flowing performance in the formwork using H-B model was validated after a comparison of SCC flowing time in the actual L-box. The latest research discovers that the concrete with high flowing such as self-compacting concrete is a shear thickening material, which is suitable to the characterization of power-law rheological models including H-B model[3].

2. H-B rheological model

Larrd.F.de[4] et al., found that fresh concrete can be described by H-B rheological model. The mathematical expression of H-B model is:

$$\tau=\tau_0+k(\partial\gamma/\partial t)^n \tag{1}$$

In Eq.1: τ is the shear stress; τ_0 is the yield stress; k is the viscosity coefficient; $\partial\gamma/\partial t$ is the shear rate; n is the power law index relating to the fluid type.

Wherein, if n=1, it is the Bingham fluid; if n＞1, it is the shear thickening fluid, and the viscosity of fluid varies with the shear stress and shear rate. When n＜1, it is the shear thinning fluid with the decreasing viscosity.

3. Back-analysis of rheological parameters of fresh SCC

The back analysis of fresh SCC rheological parameters was made using the direct method, which converts the back analysis problem of parameters into the optimal problem of a target function, successively revise the trial value of rheological parameters using the normal analysis and iterative

least error function, until the optimal value is obtained[5]. The target function is built by comparing the flowing time T_i of fresh SCC in L-box and the flowing time $T_i^{'}$ of SCC in the L-box simulation, and the optimal value of rheological parameters of H-B model was gradually obtained combining the pattern search method.

3.1 L-box test and numerical simulation of fresh SCC

L-box is the modified one, the mesh in 20mm×15mm was used to divide the side walls of the L-box, 7 feature points at 100mm, 200mm…700mm was marked. In testing the vertical part was filled in12L fresh SCC, after 1min of standing, the active door was rapidly lifted to flow the concrete mix to the horizontal part, which were done by referring to User Guide for SCC Design and Construction [6]. Meantime, the flowing time T_i of SCC flowing to 7 feature points was recorded using the stopwatch. Table 1 present the different materials and Table 2 present the results of 6 SCC groups in this test.

Table 1

Mix design of the SCC

SCC	W(kg)	C(kg)	FA(kg)	S(kg)	G(kg)	SP(kg)	SP(%)	W/(C+FA)
1	130	230	360	710	790	5.90	1.0%	0.220
2	130	230	360	710	790	5.90	1.0%	0.220
3	130	230	360	710	790	5.90	1.0%	0.220
4	130	230	360	710	790	5.31	0.9%	0.220
5	135	230	360	710	790	5.31	0.9%	0.229
6	135	230	360	710	790	5.31	0.9%	0.229

Table 2

Flow time of characteristic points measured by L - box test

SCC	T_{100} (s)	T_{200} (s)	T_{300}(s)	T_{400}(s)	T_{500}(s)	T_{600}(s)	T_{700}(s)	ρ (kg/m^3)
1	0.3	0.8	1.2	1.7	2.7	3.5	5.6	2380
2	0.6	1.2	1.9	2.7	3.8	5.2	6.9	2370
3	0.6	0.9	1.4	2.6	3.4	4.5	6.4	2350
4	0.8	1.9	2.5	3.9	5.8	8.4	12.8	2370
5	0.3	0.8	1.3	1.8	2.7	3.6	6.4	2370
6	0.5	1.0	1.5	2.0	2.9	4.4	5.4	2320

The simulation was made on fresh SCC flowing in L-box, the finite element software Fluent was operated to simply SCC as the incompressible viscous fluid. The analogue model (Fig.1) was constructed according to the actual dimension of L-box, where the number “1” means SCC, “0” means the air, and the number between “0” and “1” means the mix of these two materials.

Fluent setting for the parameter calculation: The two phase flow VOF model was used, the first, second phase was air and SCC respectively, and the material properties were defined by H-B model. The inlet condition is pressure inlet and outlet condition is the pressure outlet, the reference pressure point is standard atmospheric pressure, and the relative pressure is 0. The gravity effect at the y direction was considered.

3.2 The construction and optimization of back-analysis target function

In the actual L-box flowing test, the flowing time T_i at 7 feature points were determined. As the time was very little at T_{100}, but the human error was bigger, so the remaining 6 feature points were selected. The target function was established according to the least square method:

$$f(x)=\sum_{i=200}^{700}(T_i^{'}-T_i)^2 \tag{2}$$

In Eq.2, $T_i^{'}$ means the time of SCC flowing to the feature points in the L-box simulation test, T_i means the time of SCC flowing to the feature points in the actual L-box test. i=200mm,300mm…700mm.

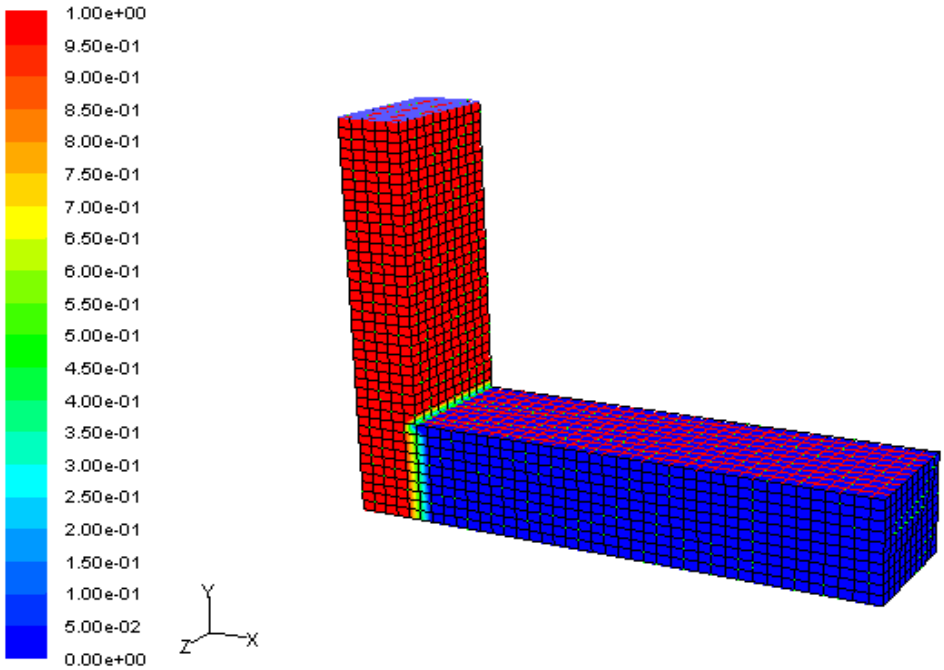

Fig.1 The three-dimensional analogue mode of L- box

Three rheological parameters τ_0, k, n to be back-analyzed were included in $T_i^{'}$ and T_i, the finite element normal analysis was made to trial-calculate the target function value in a stepwise way according to the given rheological parameters, until the flowing time at 6 feature points in simulation was basically consistent with the flowing time at the actual L-box feature points, namely the rheological parameters when the optimal value solved in Eq.2 was exactly the value obtained from the back-analysis.

Table 3

Flow time of characteristic points measured by L - box test

SCC	(τ_0,a,b)	$T_{200}^{'}$ (s)	$T_{300}^{'}$ (s)	$T_{400}^{'}$ (s)	$T_{500}^{'}$ (s)	$T_{600}^{'}$ (s)	$T_{700}^{'}$ (s)	$f(x)$
1	(190,45,1.16)	0.72	1.19	1.80	2.66	3.85	5.34	0.208
2	(240,61,1.25)	1.01	1.66	2.49	3.67	5.24	7.16	0.224
3	(250,60,1.05)	0.79	1.33	2.06	3.17	4.72	6.64	0.468
4	(280,111,1.10)	1.48	2.51	3.91	5.96	8.80	12.42	0.507
5	(220,52,1.09)	0.74	1.23	1.88	2.84	4.18	5.90	0.621
6	(180,46,1.20)	0.80	1.31	1.97	2.88	4.15	5.71	0.236

The pattern search method was introduced during the process of seeking the optimal solution in Eq.2. The pattern search method alternatively executed two searches: axial search and pattern search, from the given starting point. As to the solution to three parameters problem in H-B model, τ_0, k and n were set as three directions of the space rectangular coordinate system x, y and z, where e_1=(1,0,0), e_2=(0,1,0), e_3=(0,0,1); the search was done along e_1, e_2 and e_3 respectively, and the specific steps were shown in Reference [7]. After several iterative calculations, 6 groups of test results were ultimately obtained (shown in Table 3).

The comparison between Table 3 and Table 2 suggests that the flowing time in simulation was basically consistent with the measured value. For example, it can be shown in the comparison figure (Fig.2 and Fig.3) when Group 5 SCC flew to 400mm. The test errors can be mainly attributed to: The measured time in L-box test was only accurate to 0.1S, while it was accurate to 0.01S in simulation. In addition, there was some difference as to the slip boundary walls between the simulation and actual test.

Fig.2 The time of SCC flow to 400 mm distance T_i=1.80S

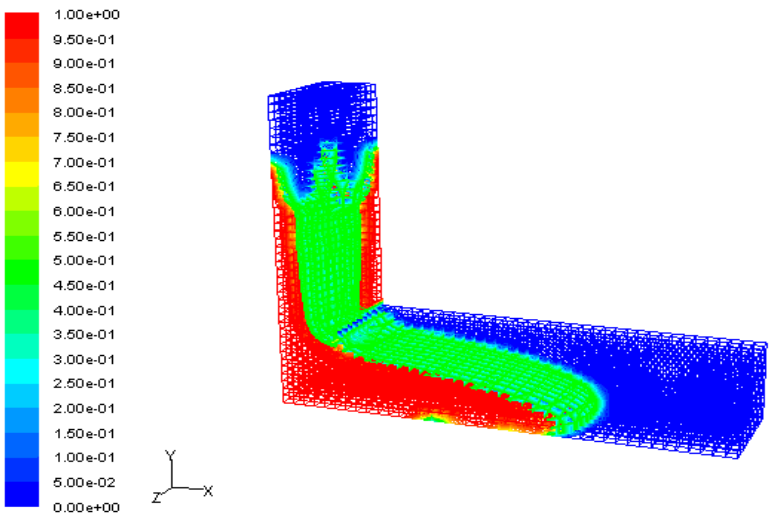

Fig.3 The time of SCC flow to 400 mm distance $T_i^{'}$=1.88S

3.3 V-funnel verification test and analysis

The V-funnel test and the V-funnel numerical simulation were compared after 6 groups of rheological parameters were obtained from the back analysis. The V-funnel test process was referred to the *SCC Applied Technology Procedure*[8], fresh SCC corresponds to the SCC used in the L-box test as previously described, and the final time of SCC flowing through the V-funnel was recorded. Then the rheological parameters τ_0, k and n obtained from the back analysis were used as the known inputs to conduct the V-funnel simulation test. The test results are given in the following Table4.

Table 4

V-funnel test validation results

SCC	trial value $T_v(s)$	Simulation value $T_v^{'}(s)$	Absolute error (s)	relative error (%)
1	11.8	10.0	-1.8	15.20%
2	14.7	13.3	-1.4	9.50%
3	14.5	14.3	-0.2	1.37%
4	22.5	20.8	-1.7	7.50%
5	11.3	10.3	-1.0	8.84%
6	12.3	10.9	-1.5	12.10%

Table 4 shows that the result of the simulated values is closer than that of the tested values, but all simulated values are smaller than the tested values, in which Group 1 has the biggest error with the absolute error of 1.8 seconds and the relative error of 15.20%, the possible cause is that coarse aggregate has friction and collision at the outlet during the actual V-funnel test which led to more

time of final flowing, but this was not considered in the simulation. According to the relative error, the requirements of engineering precision can be more or less satisfied, which indicates that the rheological parameters obtained from the back analysis are reliable to some extent.

4. Conclusions

The rheological parameters of Fresh SCC were examined through the theory of rheology, fresh SCC was assumed to conform to the H-B rheological model, according to the verification result of rheological parameters obtained from the back analysis, the relative error is around 10%, so it will be feasible to seek the optimization of rheological parameters through the establishment of the target function using the flowing time at different distances in the L-box test as the feature parameters.

In the V-funnel simulation verification test using the software Fluent, the rheological parameters obtained from the back analysis were used as the known inputs to measure the final flowing time of SCC through the V-funnel, it is found that the simulated values are always smaller than the tested values after the comparative analysis, the possible cause is that SCC coarse aggregate has friction and collision at the outlet during the actual V-funnel test which led to more time of final flowing, but this was not considered in the simulation.

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