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Reconstruction and Practice of Civil Engineering Materials Experiment Course under the Background of New Engineering: Integration of Virtual-Physical Fusion and Industry-Education Collaboration

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Abstract

Under the background of new engineering education, which focuses on the talent cultivation goals of “innovation ability, engineering literacy, and interdisciplinary integration”, the traditional civil engineering materials experiment course is faced with the dual dilemmas of “disconnection between virtual and physical aspects, and separation between teaching and industry”. It is difficult to meet the needs of the modern civil engineering industry for high-quality technical talents. This paper proposes a curriculum reform framework of “virtual-physical fusion + industry-education collaboration”. By constructing a three-stage experimental teaching process of “virtual simulation preview - physical experiment verification - industrial project practice”, and integrating the tripartite resources of “colleges and universities - enterprises - scientific research institutions”, the curriculum reconstruction is realized from four dimensions: teaching content, teaching mode, assessment system, and platform construction. Taking Qingdao City University as an example, this course is a professional basic course. It mainly covers the basic composition, technical performance, quality requirements, and inspection methods of common civil engineering materials. The course focuses on the properties, preparation, application methods, uses, and testing methods of civil engineering materials. Through learning, students can be familiar with the properties of common civil engineering materials, know how to select common civil engineering materials, and understand certain knowledge of storage and preservation; they can reasonably select and correctly use materials according to different engineering *conditions, establish a good engineering awareness, and have the basic ability to analyze engineering quality problems caused by materials and put forward corresponding improvement measures, as well as the skills to conduct performance testing and quality evaluation of common civil engineering materials in engineering; students should have basic professional literacy and a good sense of work discipline, a scientific attitude of being serious and careful in work, a certain ability of teamwork, and be able to reasonably divide work according to work tasks, help each other, and complete tasks collaboratively. This reform plan provides a replicable and promotable practical path for the quality improvement and upgrading of the civil engineering materials experiment course under the background of new engineering.*

Keywords

New Engineering; Civil Engineering Materials Experiment, Virtual-Physical Fusion, Industry-Education Collaboration, Curriculum Reconstruction; Engineering Literacy

1. Introduction

The 2024 *China Civil Engineering Industry Development Report* points out that China’s civil engineering field is accelerating its transformation towards “greenization, intelligence, and industrialization”. The annual application proportion of new materials such as ultra-high performance concrete (UHPC), recycled aggregate concrete, and fiber-reinforced polymer (FRP) increases by 12% on average. At the same time, new technologies such as “Building Information Modeling (BIM) + non-destructive testing” and “digital twin + material performance monitoring” are reconstructing the material testing process. This transformation puts forward higher requirements for the “practical innovation ability, industrial adaptation ability, and technology integration ability” of civil engineering professionals.

The “New Engineering” education concept, which emphasizes “taking industrial needs as the orientation and technological innovation as the driving force”, provides a direction for solving the above contradictions. “Virtual-physical fusion” is not a simple superposition of “virtual + physical”, but uses virtual simulation to solve the “impossibility” of physical experiments, and then verifies the “authenticity” of virtual results through physical operations, forming a closed loop of “virtual preview - physical verification - virtual-physical complementarity”; “industry-education collaboration” breaks through the limitation of colleges and universities as a single teaching subject, and transforms the real projects, testing standards, and technical equipment of enterprises into teaching resources, realizing the synchronization of teaching content with industrial needs and the matching of ability cultivation with post requirements. Based on this, this paper constructs a curriculum reform framework of “virtual-physical fusion + industry-education collaboration”, verifies its effectiveness through systematic practice, and provides a new paradigm for the reform of the civil engineering materials experiment course.

2. Diagnosis of Existing Problems in Traditional Civil Engineering Materials Experiment Courses

In order to accurately locate the starting point of reform, this paper conducts a survey on the civil engineering materials experiment courses of 8 domestic colleges and universities (including “Double First-Class” universities, provincial undergraduate colleges, and application-oriented undergraduate colleges) (including curriculum syllabus analysis, teacher-student interviews, and enterprise feedback), and summarizes the following four types of core problems combined with its own teaching practice:

2.1 Insufficient Coverage of Experimental Scenarios and Lack of Virtual-Physical Linkage

The traditional course is dominated by “physical experiments, supplemented by virtual experiments”, and the two are independent of each other. Moreover, physical experiments can only cover “basic verification” projects (such as cement soundness testing and concrete compressive strength testing), accounting for less than 40% of the actual material testing scenarios in engineering; while “complex engineering” projects (such as concrete strength attenuation tests under fire and fatigue performance tests of bridge bearing materials) cannot be carried out in university laboratories due to “high risk, long cycle (for example, freeze-thaw tests require 300 cycles and take 15 days), and large equipment investment (the cost of a single concrete freeze-thaw testing machine exceeds 500,000 yuan)”. The existing virtual experiments are mostly “animation demonstration type” (such as the simulation of concrete mixing process), lacking “interactivity” and “data linkage”. Students can only “watch the operation” and cannot find problems that may occur in physical experiments through virtual preview (such as insufficient strength caused by wrong mix ratio calculation).

2.2 Teaching Content Lags Behind the Industry and Industry-Education Resources Are Separated

Disconnection of technical standards: The old version of standards before 2019 (such as GB/T 50081-2011 *Standard for Test Methods of Physical and Mechanical Properties of Concrete*) are still used in teaching, and new contents such as “testing methods for impurity content of recycled aggregates” in the 2023 updated *Technical Standard for Application of Recycled Aggregate Concrete* (GB/T 50743-2023) are not included, resulting in deviations between the testing methods mastered by students and the actual operations of enterprises.

Lack of industrial projects: Most experimental projects are “closed verification questions” (such as “determining the compressive strength of concrete with a given mix ratio”), lacking “open questions” in real enterprise projects (such as “the bearing ratio of a municipal road base material is not up to standard, how to locate the cause through material testing”), making it difficult for students to form “engineering problem thinking”.

Idle enterprise resources: Most of the interviewed enterprises stated that they are “willing to provide testing equipment and project resources”, but due to the lack of a collaboration mechanism, it is impossible to establish a stable experimental teaching cooperation with relevant enterprises, resulting in the failure of enterprises’ “on-site testing data”, “fault cases”, and “new equipment” to be transformed into teaching resources of the university.

2.3 Rigid Teaching Mode and Insufficient Student Subjectivity

The traditional course adopts a linear mode of “teacher explanation → student imitation → report submission”, and students are in a state of “passive acceptance”. The survey shows that 65% of students said that “they did not preview in depth before the experiment and only operated according to the steps given by the teacher”; 42% of students could not independently analyze the reasons (such as material measurement errors and insufficient maintenance conditions) when the experimental data was abnormal (such as concrete strength lower than the design value); 37% of students believed that “the experimental report only needs to organize data and does not need to be related to engineering applications”, leading to “disconnection between operation and thinking, and disconnection between experiment and engineering”.

2.4 Single Assessment System and One-Sided Ability Evaluation

The existing assessment is centered on the “experimental report” (accounting for more than 60%), supplemented by “attendance” (accounting for 30%), and has obvious defects: First, it ignores process evaluation and cannot reflect students’ “standardization of equipment operation”, “teamwork ability”, and “problem-solving ability”. For example, a student who makes mistakes in experimental operations but completes the report by plagiarizing data can still get a high score; second, there is a lack of industry-oriented evaluation, and “whether it meets enterprise testing standards” and “whether it can solve on-site problems” are not included in the assessment, resulting in the mismatch between students’ “experimental ability” and “post requirements”; third, innovation evaluation is lacking, and no incentives are given to students’ “suggestions for improving experimental methods” and “exploration plans for new materials”, which inhibits the sense of innovation.

3. Design of Curriculum Reconstruction Framework for “Virtual-Physical Fusion + Industry-Education Collaboration”

In response to the above problems, guided by the “New Engineering” education concept, this paper constructs a curriculum reconstruction framework of “virtual-physical fusion + industry-education collaboration”, and realizes the four-dimensional upgrading of “teaching content, teaching mode, assessment system, and platform construction” through the three-stage linkage of “virtual simulation - physical experiment - industrial practice” and the tripartite collaboration of “colleges and universities - enterprises - scientific research institutions”.

3.1 Reconstruction of Teaching Content: A Dynamic System Based on “Industrial Needs + Technological Iteration”

A “curriculum content reform team” is established by combining “colleges and universities + enterprises + scientific research institutions”, and a three-stage content system of “basic module - advanced module - practical module” is constructed to realize the matching of “virtual content with physical content and the synchronization of teaching content with industrial technology”:

Table 1. Assessment System Table

Module Type	**Core Goal**	**Virtual-Physical Fusion Content Design**	**Industry-Education Collaboration Resource Support**
Basic Module (40%)	Master standardized operation and basic principles	Virtual: BIM modeling to preview material testing processes (such as sand and gravel gradation screening) and simulate equipment operation errors (such as pressure machine overloading); Physical: Verification experiments (cement setting time, concrete cube compressive strength)	Enterprises provide the latest testing standards (such as GB/T 175-2023 *Common Portland Cement*) and equipment operation videos
Advanced Module (30%)	Cultivate the ability to adapt to complex scenarios	Virtual: Digital twin to simulate the performance changes of concrete under high temperature (temperature field - strength field coupling) and optimize the mix ratio of recycled aggregate concrete; Physical: Exploratory experiments (the influence of water-cement ratio on concrete impermeability, FRP material tensile performance testing)	Scientific research institutions provide samples of new materials (such as UHPC and basalt fiber) and a testing data sharing platform
Practical Module (30%)	Improve the ability to solve engineering problems	Virtual: Engineering case simulation (such as material testing and diagnosis of concrete cracks in a bridge) and virtual deduction of on-site testing schemes; Physical: Real enterprise projects (such as concrete rebound testing of community garages, road base CBR tests)	Enterprises provide on-site testing tasks, engineer guidance, and testing report templates (such as *Construction Engineering Material Testing Report*)

At the same time, a “dynamic content update mechanism” is established: a “industrial technology seminar” is held every semester to incorporate the latest testing technologies of enterprises (such as “drone lidar detection of concrete surface defects”) and the research results of new materials from scientific research institutions (such as “solid waste-based recycled aggregate modification technology”) into the teaching content, ensuring the “timeliness and industrial adaptability” of the teaching content.

3.2 Innovation of Teaching Mode: Interactive Teaching of "Three-Stage Linkage + Tripartite Collaboration"

Breaking the traditional linear teaching mode, a three-stage linkage teaching process of "virtual simulation preview → physical experiment verification → industrial project practice" is designed, and the tripartite collaborative guidance of "university teachers - enterprise engineers – researchers" is integrated. The specific implementation path is as follows:

3.2.1 First Stage: Virtual Simulation Preview (Before Class + In Class)

Preview before class: Through the "civil engineering materials virtual experiment platform" (independently developed, integrating BIM and digital twin technology), students complete "three major tasks": ① Simulation operation (such as previewing the concrete mix ratio calculation and mixing process, and the platform prompts wrong operations in real time, such as aggregate measurement deviation); ② Scene simulation (such as simulating "concrete slump testing during rainy construction" and analyzing the impact of environmental factors on experimental results); ③ Scheme design (designing a testing scheme on the virtual platform for the "road base material testing needs" provided by enterprises and submitting it to enterprise engineers for review).

Feedback in class: Teachers focus on explaining common problems (such as "wrong calculation of recycled aggregate moisture content") based on the "operation data report" of the virtual platform (such as students' mix ratio calculation accuracy and virtual scheme pass rate). Enterprise engineers comment on students' virtual testing schemes online and put forward optimization suggestions (such as "increasing the frequency of aggregate gradation testing").

3.2.2 Second Stage: Physical Experiment Verification (In Class)

Virtual-physical linkage operation: Students carry out physical experiments in groups (3-4 people) based on the optimized scheme from the virtual preview. For example, in the "compressive strength test of recycled aggregate concrete", the strength values under different recycled aggregate replacement rates are first predicted through the virtual platform, and then concrete is prepared in the physical laboratory according to the "virtual scheme". The deviation between the "virtual predicted value" and the "physical testing value" is compared, and the reasons are analyzed (such as the virtual platform not considering the actual moisture content of aggregates).

Tripartite collaborative guidance: University teachers are responsible for guiding "experimental principles and operation specifications", enterprise engineers are responsible for supervising "engineering standards and data authenticity" (such as reminding students to "retain parallel samples for on-site testing"), and researchers are responsible for answering questions about "new material properties and testing methods" (such as explaining the "stress mutation phenomenon" in FRP material tensile tests).

3.2.3 Third Stage: Industrial Project Practice (After Class + Holidays)

Project undertaking: Enterprises release “real testing tasks” (such as “concrete strength rebound testing of a affordable housing project” and “road base material CBR test of a park”), and student groups bid to undertake them, and are required to submit a “testing scheme (including virtual deduction report), division of labor, and time plan”.

On-site practice: Under the leadership of enterprise engineers, students enter the engineering site and complete the whole process of “sampling - testing - data sorting - report writing”: ① Sampling (determine sampling points according to GB 50164-2011 *Standard for Quality Control of Concrete*); ② Testing (use the enterprise’s automatic rebound hammer and ultrasonic testing instrument); ③ Report submission (write the testing report in the enterprise format, which needs to include “problem analysis and suggestions”, such as “the concrete strength in a certain area is low, and it is recommended to increase the maintenance time”).

Achievement acceptance: Enterprises organize a “project acceptance meeting”, and engineers and university teachers jointly review the report. If the report meets the engineering requirements, it can be used as a “reference document for enterprise engineering quality evaluation”.

3.3 Upgrading of Assessment System: Three-Dimensional Evaluation of “Process + Ability + Industry”

Abandoning the single assessment centered on “reports”, a three-dimensional evaluation system of “process assessment (50%) + ability assessment (30%) + industry assessment (20%)” is constructed. The specific indicators and evaluation subjects are shown in the following table:

Table 2. Evaluation System Table

Assessment Dimension	Core Indicators	Evaluation Method	Evaluation Subject
Process Assessment (50%)	1) Completion of virtual preview (operation accuracy, scheme rationality); 2) Standardization of physical experiments (equipment operation, data recording); 3) Contribution to teamwork (quality of work division, communication efficiency)	1) Automatic scoring by the virtual platform + teacher review; 2) On-site observation and scoring by teachers + group mutual evaluation; 3) Mutual evaluation among group members + evaluation by enterprise engineers	University teachers, students, enterprise engineers
Ability Assessment (30%)	1) Data processing ability (identification of abnormal data, deviation analysis);	1) Scoring of physical experiment data reports; 2) Review of “problem solutions”	University teachers, researchers, enterprise engineers

Assessment Dimension	Core Indicators	Evaluation Method	Evaluation Subject
	2) Problem-solving ability (troubleshooting of experimental failures, diagnosis of engineering problems); 3) Innovation ability (improvement of experimental methods, exploration of new materials)	in industrial projects; 3) Defense of innovation schemes (such as "UHPC mix ratio optimization")	
Industry Assessment (20%)	1) Compliance of testing reports (whether they meet enterprise standards and engineering requirements); 2) Post adaptability (proficiency in on-site operations, collaboration efficiency with engineers); 3) Cognition of industrial technology (mastery of new testing technologies)	1) Acceptance scoring of enterprise testing reports; 2) On-site evaluation by enterprise engineers; 3) Industrial technology written test (including the latest standards and technologies)	Enterprise engineers

3.4 Platform Construction: Resource Support for "Virtual-Physical Integration + Industry-Education Sharing"

To ensure the implementation of the reform, a three-in-one teaching platform of "virtual simulation platform + physical experiment center + industry-education sharing base" is constructed. The specific construction path is as follows:

3.4.1 Development of Virtual Simulation Platform

Jointly with the "University School of Computer Science + Enterprise Technology Department", the "civil engineering materials virtual-physical fusion experiment platform" is developed. Its core functions include: ① BIM modeling module: It can construct a full-scenario model of "concrete mixing plant - construction site" and support students to simulate the whole process of material transportation, sampling, and testing; ② Digital twin module: Import the material performance data of actual enterprise projects (such as the strength change curve of a bridge concrete over time), and students can adjust parameters (such as maintenance temperature) to simulate performance changes; ③ Data linkage module: Connect with the "intelligent testing equipment" (such as automatic pressure testing machine) in the physical laboratory, and synchronize the physical experiment data to the virtual platform in real time, realizing a data closed loop of "virtual prediction - physical verification".

3.4.2 Upgrading of Physical Experiment Center

Equipment intelligence: Funds are invested to update “intelligent testing equipment”, such as: ① Automatic cement flexural and compressive integrated machine (which can automatically record data and generate curves); ② Concrete freeze-thaw testing machine (supporting remote monitoring of the experimental process); ③ Ultrasonic flaw detector (equipped with BIM model, which can locate defect positions), ensuring that the equipment is consistent with the model of on-site testing equipment of enterprises.

Safety standardization: Referring to the standards of enterprise laboratories, a “safety training area” is set up, equipped with eye washers, emergency rescue boxes, and explosion-proof glass, and “equipment operation procedures (including enterprise version)” are posted to cultivate students’ “industrial-level safety awareness”.

3.4.3 Construction of Industry-Education Sharing Base

Jointly with 3 large-scale construction enterprises and 2 scientific research institutions, the “civil engineering materials industry-education sharing base” is built to realize “two-way flow of resources”: ① Enterprises provide “equipment sharing” (such as large-scale freeze-thaw testing machines and scanning electron microscopes) and “project sharing” (annual testing tasks); ② Colleges and universities provide “technical training” (conducting “new material testing technology” training for enterprise employees) and “scientific research support” (jointly carrying out research on “performance optimization of recycled aggregate concrete”); ③ The base opens an “enterprise engineer studio” to students, allowing students to consult engineering problems at any time and participate in enterprise technical meetings.

4. Reform Practice and Effectiveness Analysis

4.1 Practice Objects and Schemes

Taking the 2023-level students of the civil engineering major of Qingdao City University as the research object, a “controlled experiment” design is adopted:

Reform group: 60 students, adopting the curriculum framework of “virtual-physical fusion + industry-education collaboration”, and completing the whole-process learning of “basic module (virtual preview + physical verification) → advanced module (digital twin simulation + new material experiment) → practical module (enterprise road base testing project)”;

Control group: 60 students, adopting the traditional teaching mode, and completing the conventional process of “teacher explanation → physical verification experiment → report submission”.

The practice cycle is 1 academic year (2023-2024 academic year), and the effectiveness is evaluated through four-dimensional indicators: “operation assessment, ability test, enterprise feedback, and student questionnaire”.

4.2 Analysis of Practice Effectiveness

4.2.1 Significant Improvement in Experimental Operation Ability

Through the “on-site operation assessment” (assessment project: concrete mix ratio design and compressive strength testing), the operation standard rate and data accuracy rate of the two groups of students are compared:

Operation standard rate: 92% of the reform group (only 5 students had “aggregate measurement deviation” and “wrong operation sequence of pressure machine”), and 68% of the control group (20 students had operation errors, such as “not calibrating the pressure machine” and “improper control of maintenance conditions”);

Data accuracy rate: The deviation rate between the experimental data and the theoretical value of the reform group is less than 5% (meeting the enterprise testing standards), while that of the control group is higher than 12%, mainly due to “failure to find the mix ratio calculation error through virtual preview in advance”.

This shows that the linkage mode of “virtual preview - physical verification” can effectively reduce operation errors and improve data reliability.

4.2.2 Obvious Enhancement in Engineering Problem-Solving Ability

An “engineering problem test” is designed (case: in the concrete strength testing of a community garage, it is found that the strength of 3 areas is lower than the design value, and students are required to analyze the reasons and put forward solutions), and the performance of the two groups of students is compared:

Reform group: 85% of the students can analyze the reasons from three dimensions: “material mix ratio (learned the relationship between mix ratio and strength in virtual preview), maintenance time (contacted on-site maintenance requirements in enterprise projects), and testing methods (mastered the key points of rebound hammer calibration)”, and put forward feasible suggestions of “increasing parallel testing and extending maintenance time”, with an average score of 82 (out of 100);

Control group: Only 40% of the students can point out the “mix ratio problem”, and no suggestions are put forward in combination with engineering practice, with an average score of 55.

This verifies the role of “industrial project practice” in cultivating students’ engineering thinking.

4.2.3 Significant Improvement in Enterprise Satisfaction

Cooperating enterprises are invited to evaluate the “post adaptability” of the two groups of students (evaluation indicators: proficiency in on-site operations, standardization of reports, and problem communication ability):

Reform group: 89% of the students received an evaluation of “good or above”, among which 30 students were rated by enterprises as “able to directly participate in on-site testing work”. Enterprises feedback that “students can quickly understand testing standards, reports meet engineering requirements, and no additional training is needed”;

Control group: Only 52% of the students received a “qualified” evaluation. Enterprises feedback that “students lack on-site experience, reports do not include engineering suggestions, and need 6 months of on-the-job training to work independently”.

4.2.4 Improvement in Students’ Learning Experience and Innovation Awareness

Through the “student satisfaction questionnaire” (120 copies distributed, 120 copies recovered), the feedback of students in the reform group is as follows:

Course satisfaction: 95% of the students believe that “virtual simulation can avoid operation risks in advance, and enterprise projects make learning more meaningful” (the satisfaction rate of the control group is 62%);

Innovation willingness: 78% of the students said that they are “willing to participate in the exploration of new materials (such as UHPC performance optimization)”, among which 15 students formed teams to apply for “college students’ innovation and entrepreneurship projects” (only 8 students in the control group have innovation willingness, and no project applications).

5. Conclusions and Prospects

5.1 Reform Conclusions

The curriculum reconstruction framework of “virtual-physical fusion + industry-education collaboration” proposed in this paper effectively solves the problems of “disconnection between virtual and physical aspects and separation between industry and education” in the traditional civil engineering materials experiment course through the “three-stage teaching process (virtual - physical - industry), tripartite resource integration (colleges and universities - enterprises - scientific research institutions), and four-dimensional system upgrading (content - mode - assessment - platform)”, and achieves three major breakthroughs:

Scenario breakthrough: Covering “high-risk, high-consumption, and complex” engineering scenarios through virtual simulation, and verifying virtual results through physical experiments, realizing “full-scenario coverage + high credibility”;

Ability breakthrough: Upgrading “operation ability” to “engineering problem-solving ability” through industrial project practice, shortening the adaptation cycle between students and posts;

Resource breakthrough: Integrating enterprise equipment, projects, and engineer resources to form a virtuous cycle of “teaching - industry - scientific research” and improving the industrial adaptability of the course.

5.2 Future Prospects

Although the reform has achieved remarkable results, it still needs to be deepened in the following aspects:

Intelligent upgrading of the virtual platform: Introduce artificial intelligence (AI) technology to develop an “intelligent diagnosis module”, which can automatically identify errors in students’ virtual operations and push personalized improvement suggestions (such as "pushing real enterprise case analysis for mix ratio calculation errors");

Long-term mechanism of industry-education collaboration: Establish a "credit recognition system between colleges and universities and enterprises". The testing projects completed by students in enterprises can be converted into course credits, and enterprise engineers' participation in teaching can be counted into "vocational skills training hours" to strengthen the cooperation motivation of both parties;

Integration of international perspective: Align with the needs of "the Belt and Road" civil engineering projects, add experimental modules of "international material standards (such as American ASTM standards)" to the virtual platform, and introduce overseas enterprise cases (such as recycled aggregate concrete application projects in Southeast Asia) to cultivate students' international engineering capabilities.

In the future, with the iteration of "digital twin + AI" technology and the deepening of industry-education integration, the framework of "virtual-physical fusion + industry-education collaboration" will continue to be optimized, providing stronger support for the high-quality development of the civil engineering materials experiment course under the background of new engineering.

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