Issues and Solutions in the Application of Warm-box Inorganic Binder on production of Aluminum Casting

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Abstract: The two-component warm-box inorganic binders have been developed and applied on mass production of aluminium castings for more than 20 years. However, extensive practices suggest that there are still challenges in sand flowability, collapsibility, casting porosity, reclamation efficiency, and moisture resistance. For these challenges, we have been trying to improve the properties of warm-box inorganic binders, and also made great progress. The comparative study on the application properties of SQ and European inorganic binder indicates that the SQ inorganic binder can absolutely replace the foreign binder for large-scale production of castings. The SQ inorganic binder demonstrates exceptional flowability, collapsibility, and minimal gas emission characteristics, making it highly effective in addressing common casting defects such as sand adhesion, incomplete sand core formation, and gas porosity frequently encountered in cylinder head and sub-frame aluminium castings.

Keywords: Inorganic Binder; Casting aluminum alloy; Warm-box; Sand core

1 Introduction

Inorganic binders have attracted a lot in recent decades in foundry. It is not only for its environmental benefit, but also for the technology demand [1].Since 1990s, researchers and commercial supplier have been managing to modified silicate aiming to develop an inorganic binder suitable for large-scale production of casting. The year 2003 marked a turning point at GIFA International Foundry Trade Fair, when new two-component inorganic binder systems were introduced, including those based on water glass. Several years later, these two-component systems were successfully implemented in the large-scale production of aluminum engine blocks and heads. The new two-component binders had created really new possibilities and prospects for the widespread introduction of inorganic binders [2].

Warm box process is more suitable for this two-component inorganic system, which features low emissions and satisfies the green foundry practices. This technology has been applied to the high-volume production of aluminum alloy automotive castings, with progressive adoption underway at globally renowned foundry enterprises (e.g., Nemak, GF Casting Solutions) across major automotive manufacturing regions including Germany's Automotive Cluster Baden-Württemberg and Michigan's Auto Alley [3-6].

Although the two-component inorganic binders realized the application of inorganic binders in mass production of aluminum castings, their inherent reactive nature still presents certain limitations. Through extensive practice, we have identified persistent challenges in molding sand flowability, sand adhesion on casting (penetration or burn-on), gas porosity, collapsibility, reclamation efficiency, and moisture resistance with the two-component inorganic binder systems. To address these issues, we have modified the two-component inorganic binder system, and conducted comprehensive application validation and comparative analysis against the predecessor product in this work.

2 Commercial warm-box inorganic binder and properties

The most popular inorganic binder system used for warm-box process is a two-component system containing silicate liquid materials and powdered additives. The two-component binder system allows the chemical reactions between powdered additives and silicate liquid materials, therefore can achieves performance comparable to resin sand. Unlike single-component inorganic binder curing systems, this two component system enables hardening not only through moisture migration and desiccation but also via inter-component chemical reactions [7]. Consequently, the incorporation of the second component could enhance curing rate, immediate strength, and ultimate strength. This innovation allows substantial reduction in inorganic binder dosage with the core strength equivalent to the high-strength organic binder sand cores, which naturally would improve the molding sand flowability.

Although the two-component inorganic binder was introduced by European suppliers twenty years ago, casting practices have shown that it still has shortcomings due to its inherent reactive nature. Being the leading manufacturers of foundry binders in Asia, SQ has launched warm-box inorganic binder products: SWB (binder) + BL (powder additives) series aiming to resolve the issues with existing products, which have been applied on in mass production of automotive aluminum castings.

The recommended dosage of SWB + BL series inorganic binder: silicate binder 1.8~2.3 wt.% of sand; powder mixture 0.8~1.2% of sand, and the specific dosage depends on the sand core type. It should be addressed that the powder is a promoter to improve the flowability, strength, hygroscopic properties and so on, so there are several series can be chosen for different aim. In the core making process the recommended core box temperature 150~180 °C, and purge air at 200~240 °C for 40~90 sec.

The properties of inorganic binder system depend not only on the binder but also on the powder additives, so a series of binder and powder are always designed. Ideal properties always rely on the sophisticated design and matching of binder and powder additive.

Comparative study on properties of inorganic binder system form different leading suppliers has been carried out, where the process parameter are: core box temperature 160 °C, blow 250°C air for 50 s. As shown in Table.1, it can be seen that the SWB200+BL505 binder is of the highest strength at every storage period (immediate, 1 h, 24 h (ambient), 24 h at constant 25°C/70%). The SWB200+BL404 presents a highest strength at 24 h (constant 25℃/70%). It suggests that the core strength depend greatly on the powder additives, so different kinds of powders should be supplied to satisfy different property demand. The products of SQ are of the best comprehensive properties, especially the high flowability and strength which are favorable for the strength and integrity of the sand core to be made, and can fully serve as a substitute for European products.

Table 1. Properties of inorganic binders from different supplier

Supplier	Warm-box binder dosage	Bending strength(MPa)				Flowability (φ16 mm/g)	Gas evolution at 750°C (g/ml）
		Immediate	1 h	24 h (Ambient)	24 h constant humidity (25°C/70%)		
European supplier A	2.2%Binder+1.0% Powder ①	1.555	3.616	1.636	0.527	5.26	7.37
	2.2%Binder+1.0%Powder ②	1.608	3.143	1.432	0.627	5.47	5.47
European supplier B	2.2% Binder+1.0% Powder	1.309	2.372	1.096	0.786	5.34	6.20
SQ	2.2%SWB200 binder +1.0%BL404 Powder	1.614	3.653	1.621	0.947	7.54	6.15
	2.2%SWB200 binder +1.0%BL505 Powder	1.713	3.806	1.661	0.673	8.12	6.10

3 Shortcomings of the existing warm-box inorganic binder and solutions by SQ in casting practice

Although the warm-box inorganic binders have been used for mass production of aluminum castings for more than twenty years, but there are still some unsolved shortcomings attributed to the inherent reactive nature of inorganic binder in production practice. Through extensive casting practice, we have identified and summarized the main shortcomings: low molding sand flowability, sand adhesion on casting (penetration or burn-on), generate gas porosity, bad collapsibility, low reclamation efficiency, and weak moisture resistance. Meanwhile, solutions have been raised based on the SWB + BL series inorganic binder to successfully solve the issues in production process.

3.1 Sand adhesion and gas porosity issues in production of casting cylinder head

Inorganic binders are alkaline, making them prone to react with molten aluminum during the casting process, which can lead to sand adhesion defects in aluminum alloy castings. Additionally, during the casting process of aluminum alloy castings, moisture in inorganic binder sand can react chemically with molten aluminum, generating hydrogen gas. Therefore, controlling moisture content in the sand mold is critical. Unfortunately, the crystalline water in water glass (sodium silicate) evaporates at 325°C, making it difficult to remove under conventional conditions. For example, a cylinder head casting producer from Zhengzhou China originally uses European inorganic binder and frequently faces the sand residue adhered on the casting internal surface, as shown in Fig.1(a)(b). Meanwhile, the porosity rate is unstable, sometimes can reach as high as 20%, and the diameter of a single gas pore tested by X-ray can reach 25 mm as shown in F.2(a).

For the two-component inorganic binders, adding certain special materials to component II (powdered additives) can create a barrier between the molten aluminum and the sand mold, thereby inhibiting the reaction and resolving the sand adhesion issue. Some other special additives in component II can also absorb the released crystalline water during high-temperature pouring, thereby reducing the reaction between moisture and aluminum to eliminate the generation of gas pore. The BL404 component II of SQ is a carefully designed multicomponent mixture containing special materials to solve the sand adhesion and gas pore. To solve the issues happened on cylinder head casting, 2.3%SWB200+ 1.0%BL404 inorganic binder system from SQ was chosen as alternative. The comparative properties are shown in Table.2. It is seen that the binder dosage and strength from the two suppliers are almost equal. The sand cores using the SQ binder system are of good integrity and surface quality, as shown in Fig.3. After casting and shakeout, the surface of casting is very clean as shown in Fig.1(c)(d), that is, the 2.3%SWB200+ 1.0%BL404 binder system almost solved the sand residue issue. Meanwhile, the gas pore almost eliminated, and only several castings has small pore whose diameter is only 5 mm as shown in F.2(b).

Table 2. Properties of sand mixtures with inorganic binder from SQ and original European supplier

Binder supplier	Warm-box binder dosage	Bending strength (MPa)			
		Immediate	1h	24h ambient (9°C/12%)	24h constant humidity (25°C/70%)
European supplier	2.5%Binder+0.8% Powder	2.146	4.816	4.581	0.793
SQ	2.3%SWB200 binder +1.0%BL404 powder	2.170	4.854	4.479	0.833

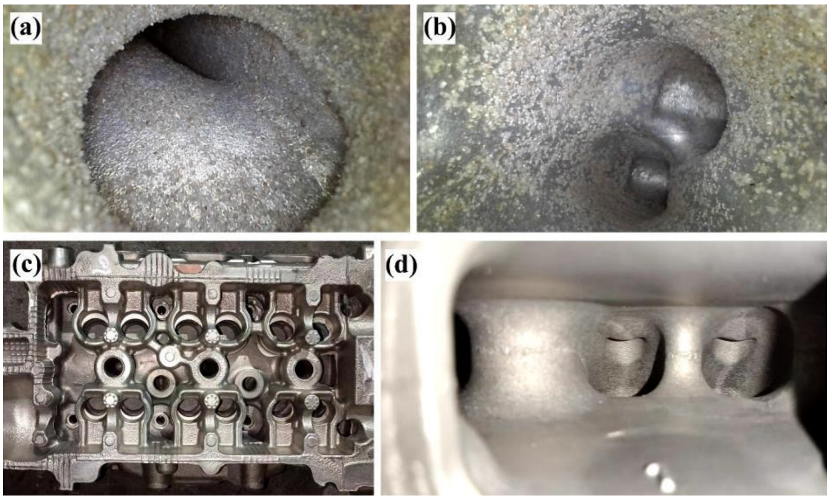


Fig. 1: Cleanness of casting internal surface. (a) (b) Sand residue adhered in the cylinder head (using European inorganic binder); (c)(d) Very clean internal surface of cylinder head without sand residue (using SQ inorganic binder)

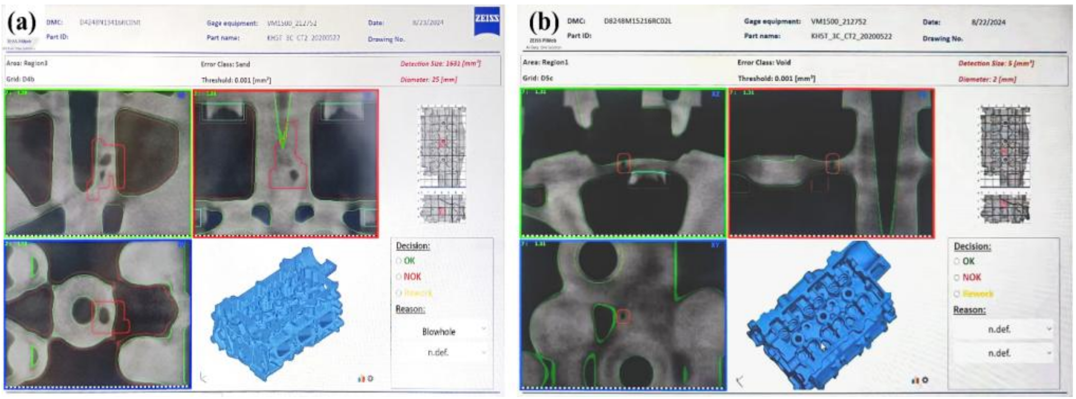


Fig. 2: Gas pore in cylinder head. (a) European inorganic binder generating φ25 mm gas pore in casting; (b) SQ 2.3%SWB200+1.0%BL404 binder system decreases the gas pore to φ5 mm

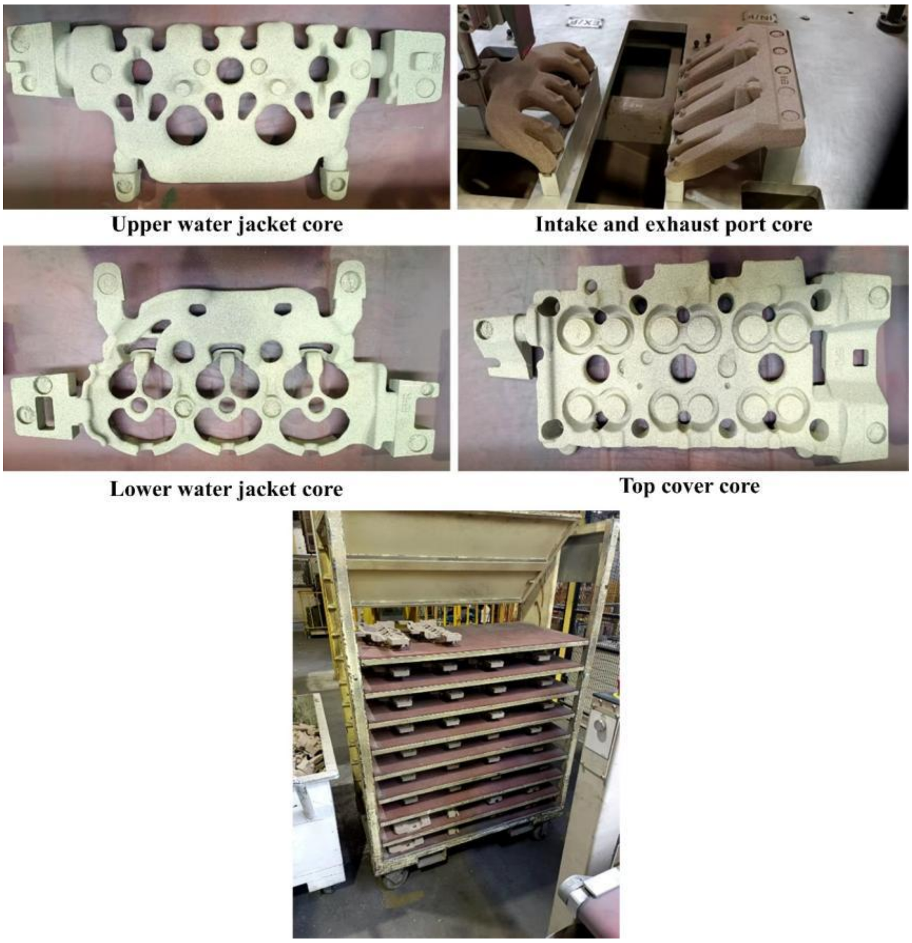


Fig. 3: Sand cores made using SQ 2.3%SWB200+1.0%BL404 binder system

3.2 Incomplete sand core caused by bad flowability of inorganic binder

Sub-frame producer in Zhejiang China using two-component warm-box inorganic binder of foreign suppliers to produce vehicle sub-frame in large-scale, but the sand core quality is unstable in integrity and collapsibility, resulting in the defect of casting and bulk core residue in casting, as shown in Fig.4.

To solve this problem, 2.0%SWB200+1.0%BL404 inorganic binder were used. The process parameters are: core box temperature 160 ℃, blow 250 ℃ air for 50 s, storage at 23℃/30%RH. The properties of sand core using binder from different supplier are shown in Table.3. Although with a dosage about 7% less than the binder from foreign supplier, 2.0%SWB200+1.0%BL404 provides a higher strength and excellent flowability. This suggests a potential improvement of the core quality in the subsequent core making process, as shown in Fig.5. Consequently, the casting quality is improved as well as the core collapsibility.

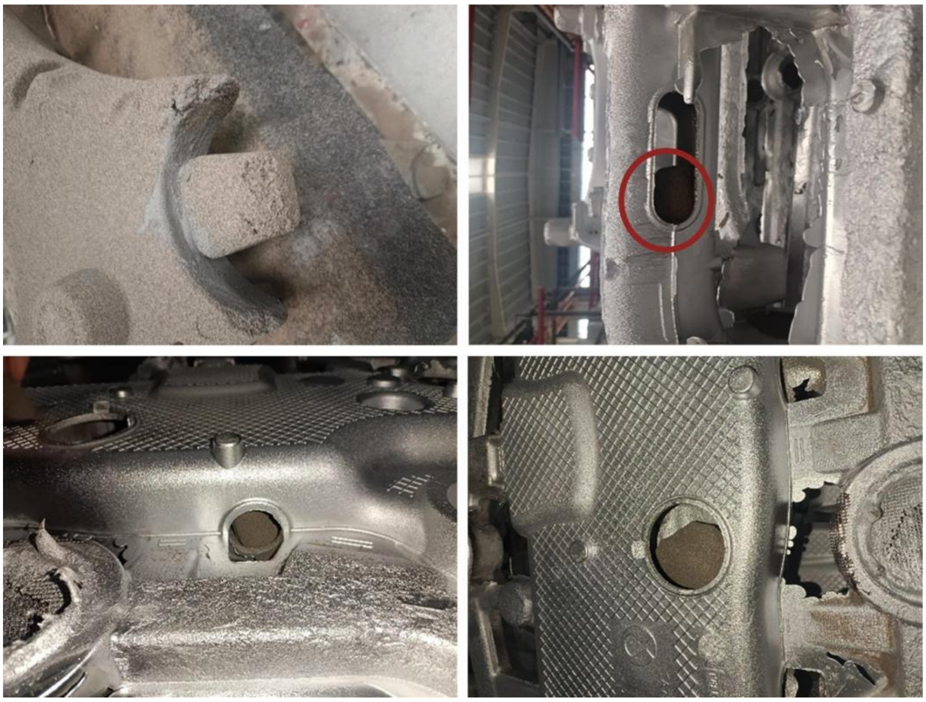


Fig. 4: Defects in sub-frame casting

Table 3. Properties of sand core for sub-frame casting with inorganic binder from different supplier

Supplier	Binder dosage	Bending strength(MPa)				Flowability (φ16mm/g)
		Immediate	1 h	24 h ambient (9°C/12%)	24 h constant humidity (25°C/70%)	
European supplier A	2.0% Binder + 1.2% Powder	1.694	4.213	3.372	0.607	6.08
European supplier B	2.0% Binder + 1.2% Powder	1.431	3.630	3.293	0.874	6.69
SQ	2.0%SWB200 Binder+1.0%BL203 Powder	1.735	4.221	3.380	0.754	8.69

Fig. 5: Improved quality of sub-frame core and casting by SQ binder

3.3 Moisture resistance

The heating-induced hardening in the inorganic binder warm box process constitutes a forced physical dehydration mechanism. During dehydration, water molecules undergo rearrangement while promoting condensation between adjacent silanol groups (Si-OH). As temperature increases, silanol groups further condense through mutual dehydration, forming siloxane bonds (Si-O-Si) that impart core strength. This process ultimately yields dehydrated silica gel. However, this dehydration hardening remains reversible - elevated environmental humidity can reverse the silicate crosslinking reactions through rehydration, leading to significant core strength degradation [8]. Figure 6 reveals the inherent humidity sensitivity of silicate systems. There is a critical humidity threshold 50% RH over which the strength at 4 h and 24 h will decrease more than 80%. Therefore, the core should be mandatorily store in constant low humidity conditions.

Water glass based inorganic binder modified by powdered promoters could enhance the hygroscopic stability. SQ has optimized the second component to further promote the hygroscopic stability of inorganic binder. Fig.7 demonstrates the proportional relationship between second component dosage and moisture resistance enhancement. Attributed to the modification of second component, the 24h strength reduction ratio was significantly decreased under varying addition levels of the second component.

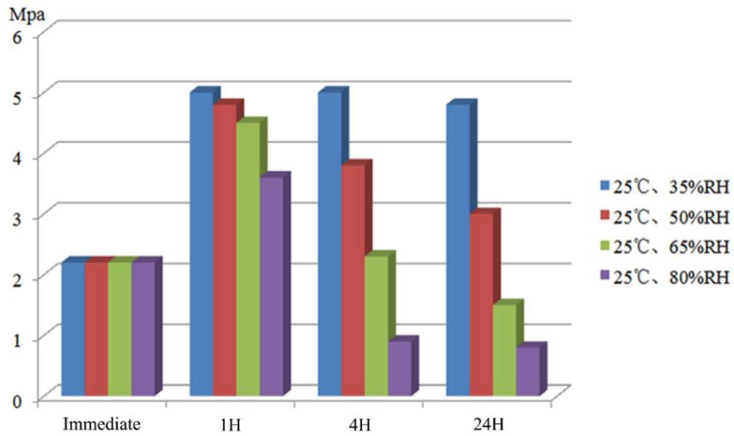


Fig. 6: The influence of humidity on core strength

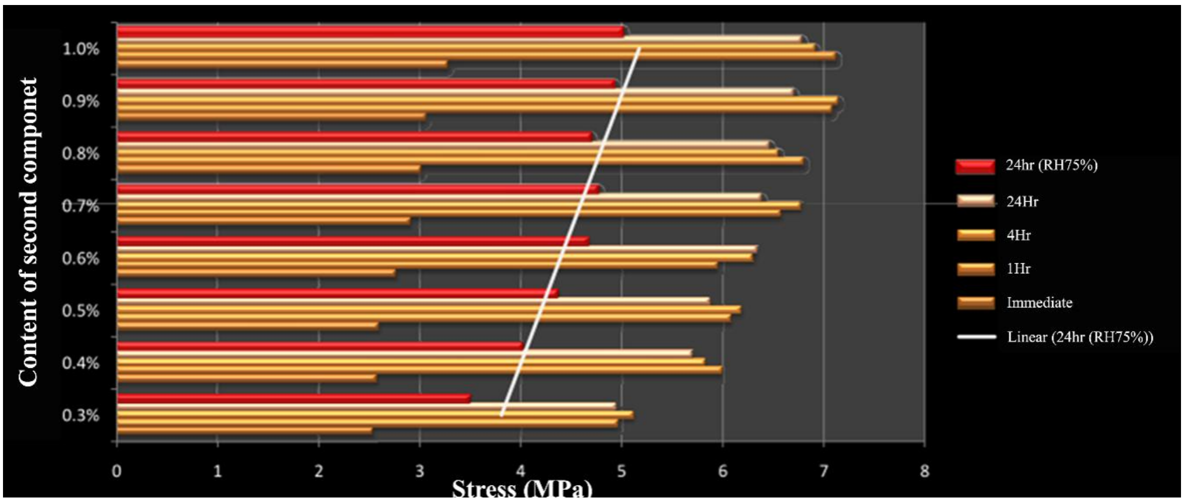
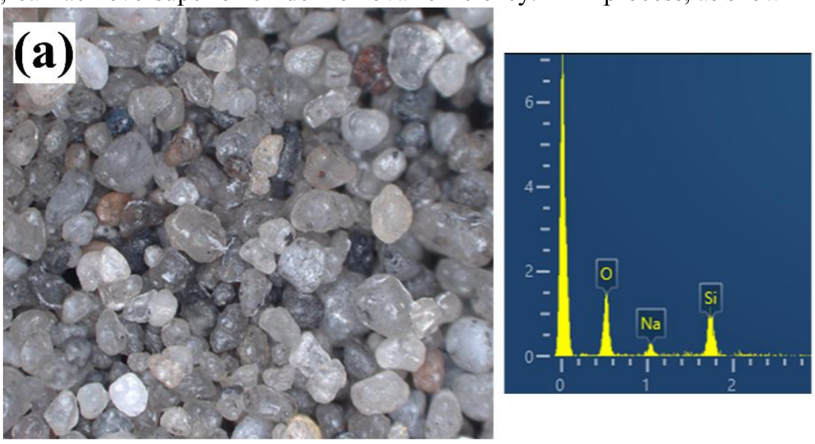


Fig. 7: Relationship between second component dosage and moisture resistance

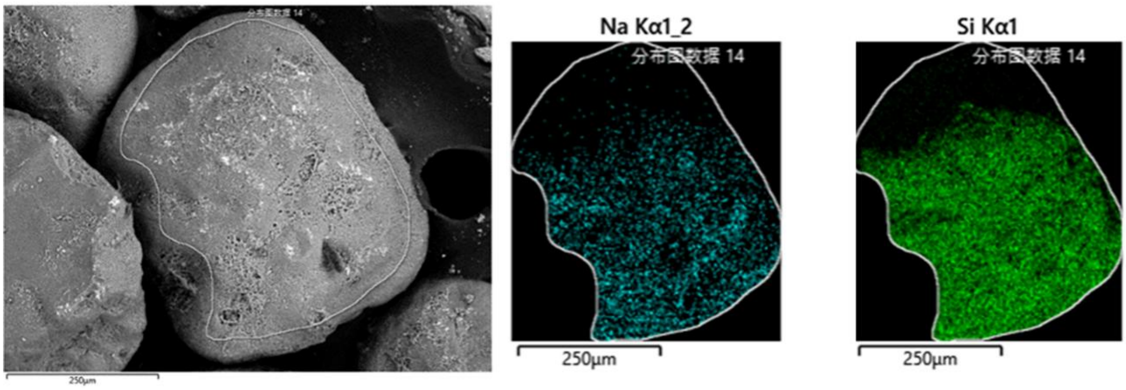
3.4 Low reclamation efficiency of traditional reclamation process

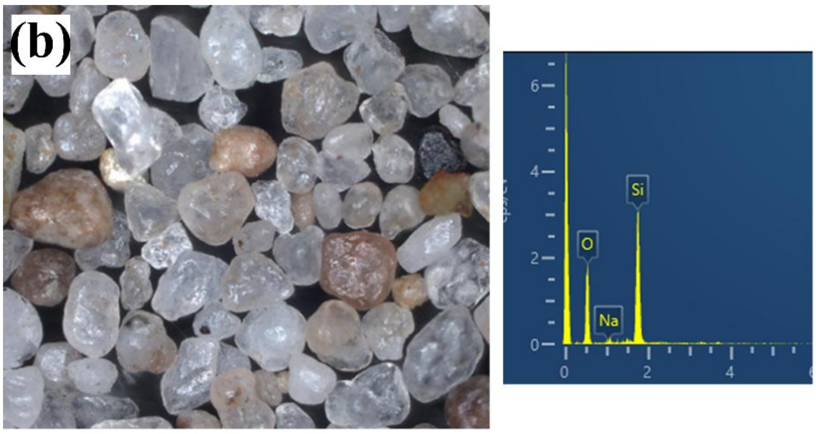
The sodium silicate in inorganic binders exhibits high reactivity with silica sand, particularly after exposure to foundry-level high temperatures. After casting, partial binder-sand interface reactions form sintered deposits that persistently adhere to sand surfaces, rendering binder reclamation an industry-wide challenge. Conventional reclamation methods, especially dry processes, often fail to effectively remove sodium silicate residues.

Based on the phase-transition characteristics of sodium silicates, S Q has developed an innovative reclamation process, can achieve superior binder removal efficiency. As demonstrated in Figure 8. Na^{+} leaching was decreased from 350 mg/L of traditional method to 100 mg/L of SQ process, as shown in Fig.8



Element	Atomic %
O	69.69
Si	25.6
Na	4.71
Totals	100





Element	Atomic %
O	67.31
Si	31.03
Na	1.66
Totals	100

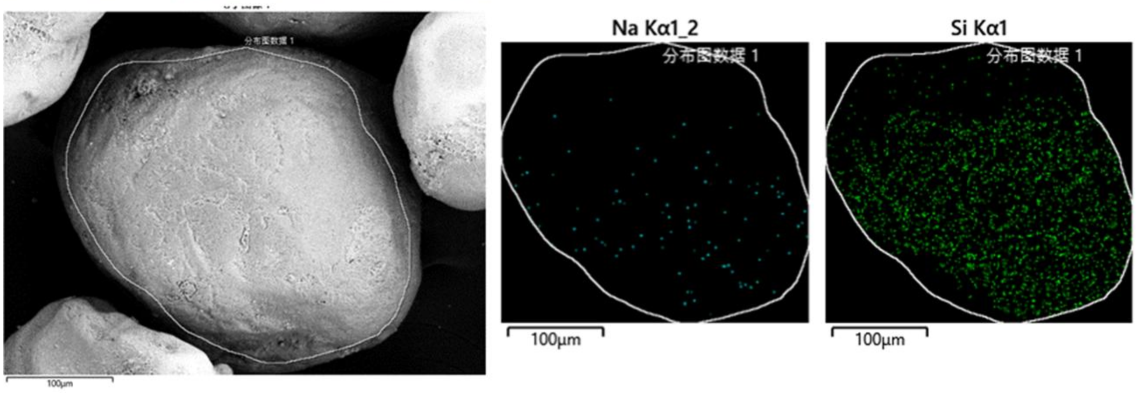


Fig. 8: Residual quantity of Na_2O on silica sand after different reclamation process. (a) Traditional method; (b) SQ reclamation process

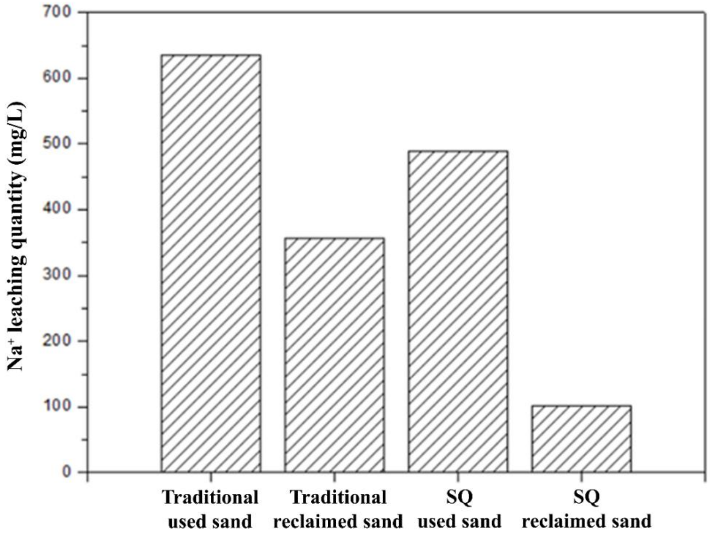
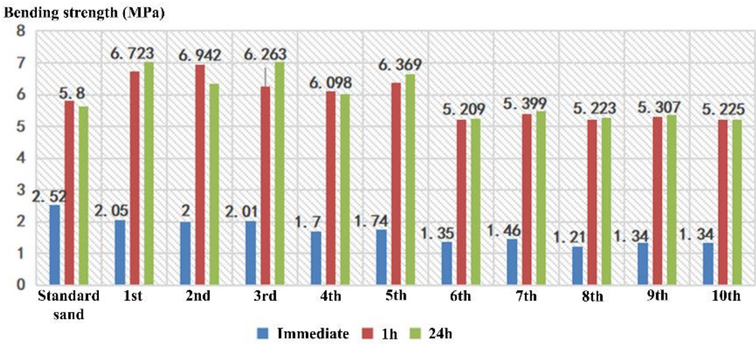


Fig. 9: Na^+ leaching quantity of different reclamation process

The adoption of the new process reduces Na^+ residue, ensuring the performance of reclaimed sand and extending its reuse cycles. As shown in Figure 10, the immediate strength of regenerated molding sand gradually decreases with increasing regeneration cycles. However, the 1-hour strength increases before 5 regeneration cycles, begins to decline after the 6th cycle, and only decreases by 9.9% after 10 regeneration cycles.



Number of cycles	Reduction percentage of bending strength compared to new sand	
	Immediate	1h
1st	18.7% decrease	15.9% increase
2nd	20.6% decrease	19.7% increase
3rd	20.2% decrease	7.9% increase
4th	32.5% decrease	5.1% increase
5th	30.9% decrease	9.8% increase
6th	46.4% decrease	10.2% decrease
7th	42.1% decrease	6.9% decrease
8th	51.9% decrease	9.9% decrease
9th	46.8% decrease	8.5% decrease
10th	46.8% decrease	9.9% decrease

Fig. 10: The influence of reclamation cycles on strength of sand core

4 Conclusions

Poor flowability, collapsibility, casting porosity, reclamation efficiency, and moisture resistance are essential the obstacles for the further application of the two-component warm-box inorganic binders. Facing these challenges, SQ has managed to develop a series of improved warm-box inorganic binders. Comparative study on the properties and application of the new inorganic binder with those from Europe indicates that the SQ binder can absolutely replace the foreign binder for large-scale production of casting.

(1) The inorganic binder of SQ has high flowability with a medium gas evolution. The flowability is almost improved by 40% comparing with those of the European supplier, which is especially favorable for the strength and integrity of the sand core to be made.

(2) Comparing with the European inorganic binder, the new product of SQ presents a high strength without increasing dosage, as well as a good flowability to ensure integrity and surface quality of sand core, consequently, solved the casting defect on sub-frame production ever using foreign binder.

(3) Attributing to the modification of the second component, the SQ binder system successfully solved the sand adhesion and gas pore issues on cylinder head casting in practice.

(4) Based on the phase-transition characteristics of sodium silicates, SQ has developed an innovative reclamation process, can achieve superior binder removal efficiency. Na^+ leaching can be decreased from 350 mg/L

of traditional method to 100 mg/L of SQ process,

Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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