The 17th East Asia-Pacific Conference on Structural Engineering & Construction (EASEC17)
27-30 June 2022 – Singapore - Towards a Resilient and Sustainable City

Experimental Study to Improve Performance of Two-Stage Concrete without Injection Focusing on the Interfacial Transition Zone

Karen Midori Masunaga[1*], Tomoki Nagoya[2], Takeshi Iyoda[3]

[1,2]Graduate School of Engineering and Science, Shibaura Institute of Technology,
3-7-5 Toyosu, Koto-ku, Tokyo, Japan, 135-8548
[3]Department of Civil Engineering, Shibaura Institute of Technology,
3-7-5 Toyosu, Koto-ku, Tokyo, Japan, 135-8548
Email: me20505@shibaura-it.ac.jp
*Corresponding author

Abstract. Two-stage concrete (TSC), also known as preplaced aggregate concrete, prepacked concrete, and rock-filled concrete, is a non-conventional concrete with an unusual construction method. It is produced by firstly placing the coarse aggregate into the formwork and after that, the voids are filled with a high-flow mortar mixture. This type of concrete has been applied in mass concrete, underwater concrete, and repair and strengthening of existing structures with economical and technical benefits. Previous studies showed that the interfacial transition zone between the coarse aggregate and the cementitious material has a primary influence on TSC, affecting the performance of hardened concrete. Also, more than the mechanical resistance of the coarse aggregate, other factors such as shape, good particle size distribution, combined with a mortar with non-shrinkage, non-segregation characteristics, and good flowability are important to achieve satisfactory performance of TSC. In this experimental study, several types of admixtures (C-S-H type hardening accelerator and three types of expansive mineral admixtures) were added to a premixed high flow mortar to improve the interfacial transition zone between aggregate and mortar of TSC blocks without injection. Measurements of porosity, air permeability coefficient, and compressive strength were conducted for TSC cores and conventional concrete specimens. Experimental results showed that the use of Calcium Oxide (CaO) expansive admixture was the most effective method evaluated and that there is a high potential to expand applications of the TSC produced without injection, as it was possible to

improve significantly both mechanical performance and mass transfer resistance, reaching similar values when compared to conventional concrete.

Keywords: Two-stage concrete (TSC); special concrete; interfacial transition zone; expansive admixtures.

1. INTRODUCTION

1.1. Two-Stage Concrete

Two-stage concrete (TSC), also known by other denominations such as preplaced aggregate concrete, prepacked concrete, and rock-filled concrete, is a special type of concrete characterized by an unconventional construction method: initially the coarse aggregates are inserted into the formwork, and then the remaining voids are filled with grout or high flow mortar. In this second stage of casting, pressurized injection method may be used but grout gravity pouring method without injection is more convenient and has economic benefits (Li et al., 2019).

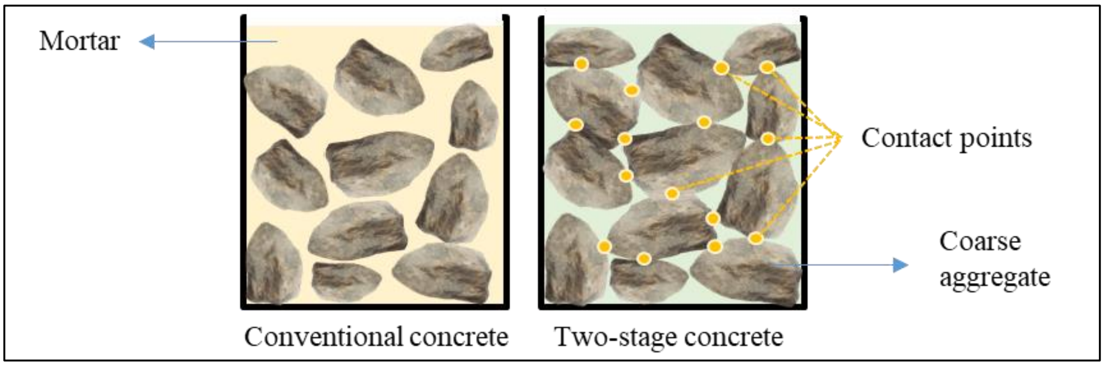


Figure 1. Direct contact of aggregates, absent in conventional concrete, significantly influences the stress transfer mechanism in two-stage concrete.

TSC has a higher volumetric aggregate ratio than conventional concrete and, thus, presents a peculiar mechanism of stress transfer, which occurs through the direct contact points of the aggregates (Figure 1). While the structural performance of conventional concrete depends on the properties of the coarse aggregate, it has been reported that the mechanical strength of the aggregate has little influence in TSC, while the texture, particle size distribution, and void ratio have a dominant effect (Najjar, Soliman and Nehdi, 2014). Moreover, to achieve superior performance for this type of concrete, a good adhesion at the interface of the aggregate with the cementitious material, also called interfacial transition zone (ITZ), is essential, since the stresses are transferred first through the coarse aggregate and later to the cementitious material. Thus, the amount and distribution of coarse aggregate, as well as the ITZ, significantly affect the axial compressive strength and mass transfer properties of TSC (An et al., 2013).

1.2 Advantages and disadvantages of TSC

The initial insertion of coarse aggregates into the formwork can make TSC an economic and sustainable concreting method because it allows the use of high quantities of coarse aggregate (cheaper) and, consequently, the reduction of cementitious material (more expensive). To achieve it, it is necessary an appropriate definition of the aggregate particle size distribution, which will reduce the void ratio. This feature results TSC having a higher modulus of elasticity when compared to conventional concrete, even for similar compressive strength values, since the modulus of the coarse aggregate is generally higher than that of the cement paste (Najjar, Soliman and Nehdi, 2014). Another positive aspect of TSC is that it only requires the transportation of coarse aggregates and grout preparation and pouring, and do not require vibration. So, the production costs related to these steps can be reduced compared to the costs of obtaining a conventional ready-mix concrete at a construction site. In addition, this construction method makes possible to reduce the heat of hydration and segregation for mass concrete.

On the other hand, to produce a good TSC a high-performance grout is essential. This means a binder material with good fluidity to fill the voids, that does not segregate and has small autogenous shrinkage – which can have an excessive cost. Otherwise, it will cause a reduction in mechanical strength and durability. It is also necessary to prepare leak-proof formworks for the flowable grout, which can also increase production costs.

Due to the challenges to balance technical and economic performance, the use of TSC is still limited, having been used mostly with injection method in large concrete structures specially in China, in underwater concreting, and in repairs and strengthening of structures where transport and concreting with conventional concrete would not be feasible (Abdelgader et al., 2015).

1.3 Enhancing TSC performance

A lot of research has been developed to improve the performance of TSC, but the attention to TSC has increased with the increasing interest in reducing cement consumption for sustainable issues and with the development of new chemical admixtures for ultra-high performance concrete (UHPC). This is because UHPC can be combined with TSC to develop a material with excellent mechanical properties, high volume of coarse aggregate and low binder consumption, especially when supplementary cementitious material are used (Li et al., 2019).

The following items were compiled by Najjar, Soliman and Nehdi (2014, 2016) to improve TSC's performance. For example, it is indicated that the size of the coarse aggregate should be at least 4 times the largest size of the fine aggregate. Also, to obtain a void ratio between 25 and 50%, it is recommended to adopt a combination of aggregates with different particle size distribution and geometries (for example, crushed material which is more rectangular combined with natural aggregate which is rounder). This will reduce the voids and increase stress transfer points. Additionally, it was verified that the use of fly ash has positive effects as a supplementary cementitious material and can reduce bleeding and that silica fume and metakaolin has a microfiller effect and pozzolanic activity, improving mechanical properties, but it reduces the fluidity. Also, it was reported that expansive admixtures, despite may reduce the strength of grout by producing voids in the cementitious material, in TSC they result in a confining effect, reducing voids that are formed mainly under the coarse aggregate (cumulated water pockets), which usually has large dimensions.

Li et al. (2019) also evaluated the effect of supplementary cementitious materials, like fly ash, metakaolin and silica fume, on the fresh and hardened mechanical properties of TSC, as well as the possibility of correlating the grout mechanical strength to the TSC mechanical strength. And to expand the applications of TSC, Yoon et al. (2015) studied the possibility of producing lightweight concrete using TSC, because with TSC pouring method a larger amount of lightweight aggregate could be preplaced without segregation. As an existing structure strengthening approach, Lee et al. (2018) and Esmaeili & Amiri (2022) recently investigated the use of TSC to transform ballasted railway tracks into slab tracks, by just pouring the cementitious grout to improve the transport capacity in a rapid and convenient way.

Considering economical and sustainable aspects, the unavoidable aging and deterioration of infrastructures and the increasing necessity of repairing and strengthening, as well as the continued use of concrete as a construction material, TSC may be a promising sustainable alternative option to conventional concrete, using large amounts of aggregates, saving cement and innovating construction methods.

A previous study showed that the ITZ between the coarse aggregate and the cementitious material exerts significant influence on the TSC, resulting in low mechanical and mass transport resistance, regardless of the type of coarse aggregate used (Shibuya & Iyoda, 2019). Also, experimental tests conducted by An et al. (2013) and Abdelgader et al. (2015) showed that the permeate paths were along the edges and that failures occurred by cracking forming around the coarse aggregate. Thus, this experimental program was conducted to improve performance of TSC without injection focusing on the treatment of ITZ. Compressive strength and mass transference properties of TSC produced using different types of admixtures were compared and analyzed.

2. MATERIALS AND METHODS

2.1 Mix design

Core samples extracted from TSC blocks were compared with conventional concrete specimens, using porosity, air permeability, and axial compressive strength tests. In conventional concrete mix design, it was used Ordinary Portland Cement (OPC) with 40% of ground granulated blast furnace slag (GGBFS) replacement; and TSC was produced using industrialized pre-mixture high flow grout which contains about 40% of GGBFS replacement. The water binder ratio (W/B) was set at 0.45.

To improve the performance of TSC without injection, Calcium silicate hydrate (C-S-H) type hardening accelerator admixture and three types of expansive admixtures were used to compensate for the adoption of concreting without injection method (Table 1 and Table 2).

The C-S-H type hardening accelerator chemical admixture (ACX) is a liquid product and was added replacing 5% of the water mass in the mix design. The expansive mineral admixtures EX1, EX2, and EX3 are solid material (powder) and were added 20 kg/m^3, only for TSC. Generally, they are added in replacement of cement, but as industrialized grout was used in the mix design of TSC, to compare the expansive admixtures effect, an extra mix design of TSC was produced by adding 20 kg/m³ of slag cement to the industrialized grout (BB). The mix design as well as the fresh state characteristics are shown in Table 3. The addition of the expansive materials reduced the fluidity of the mortar but did not compromise the workability to fill the TSC blocks. The coarse aggregate type used was common gravel with a maximum size of 20 mm for all mix designs, but for TSC particles smaller than 10 mm were also removed.

Table 1. Admixtures description

Name	Component	Information
ACX	C-S-H (Calcium silicate hydrate)	Hardening accelerator admixture with C-S-H nanoparticles that meets the JIS A 6204:2021.
EX1	Ettringite	Expansive admixtures that react with water and are used to compensate for cement autogenous shrinkage and to prevent cracks. All admixtures agree with the JIS A 6202:2017
EX2	Mixed compound ($CaSO_4 + CaO + 3CaO \cdot 3Al_2O_3 \cdot CaSO_4$)	
EX3	Calcium Oxide (CaO)	
BB	Slag Cement (Ordinary Portland Cement with 40% GGBFS replacement)	

Table 2. Expansive Admixtures Chemical Composition

Expansive Admixture	Ig loss (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	CaO (%)	F-CaO (%)
EX1	< 3.0	1.0 ~ 2.0	12.5 ~ 15.0	0.3 ~ 0.8	0.4 ~ 2.3	27 ~ 31	50 ~ 53.6	17.5 ~ 22
EX2	-	1.0	7.2	0.8	-	18.5	70.6	49.8
EX3	1.0	4.8	1.4	1.0	0.6	15.2	73.3	-

Table 3. Mix design of conventional concrete and TSC with admixtures

Concrete type		Admixture		W/B	Binder type	Fresh properties	
		Type	**Amount**			**Slump**	**Flow**
1	Conventional	-	-	0.45	OPC with 40% replacement of GGBFS	11.5 cm	-
2		ACX	5% of water mass			-	-
3	TSC	-	-	0.45	Industrialized grout (about 40% replacement of GGBFS)	-	312 mm
4		ACX	5% of water mass			-	282 mm
5		EX1	20 kg/m^3			-	299 mm
6		EX2	20 kg/m^3			-	293 mm
7		EX3	20 kg/m^3			-	288 mm
8		BB	20 kg/m^3			-	292 mm

2.2 Casting procedures and experimental tests for concrete

2.2.1 Axial compressive strength

After 3 days of sealed curing, from the rectangular concrete blocks of TSC and of conventional concrete 0.30x0.50x0.20 m, cylindrical cores were cut, with diameter D = 0.1 m and height H = 0.2 m. After that, the concrete cores were cured in water for 28 days for the axial compressive strength test (Figure 2). The mechanical performance evaluation was conducted following the JIS A 1108:2018: Method of test for compressive strength of concrete.

2.2.2 Air permeability

The cylindrical cores D = 0.1 m obtained according to item 2.2.1 were sectioned into 4 cylinders with height h = 0.05 m and dried in a chamber at 40°C temperature until stabilization of mass for the air permeability test (Figure 2). The test was conducted adapting the RILEM recommendations TC 116-PCD: 'Permeability of concrete as a criterion of its durability'. It is measured the volume of air that permeates the cylindrical specimen in a period, under a fixed pressure. The inlet pressure was set at 0.1 MPa and the air permeability coefficient was obtained according to Equation (1).

$$K = \frac{2LP_1}{P_1^2 - P_2^2} \times \frac{Q}{A} \tag{1}$$

K = Air permeability coefficient ($cm^4/N \cdot s$)
L = Thickness of specimen in airflow direction (cm)
P_1 = Inlet pressure (N/cm^2)
P_2 = Outlet pressure - atmospheric pressure (N/cm^2)
Q = Volume of permeated air (cm^3/s)
A = Permeated area (cm^2)

2.2.3 Porosity

The cylindrical specimens D = 0.1 m and h = 0.05 m used in the air permeability test were used for the determination of porosity. After o mass stabilization in a chamber at 40°C, the dry mass was obtained. After that, the specimens were saturated with water in a vacuum chamber at 0.1 MPa until complete water saturation. The saturated and submerged masses were then measured. The porosity was calculated according to the Equation (2).

$$\text{Porosity} = \frac{\text{mass}_{\text{saturated}} - \text{mass}_{\text{dry}}}{\text{mass}_{\text{saturated}} - \text{mass}_{\text{submerged}}} \quad (2)$$

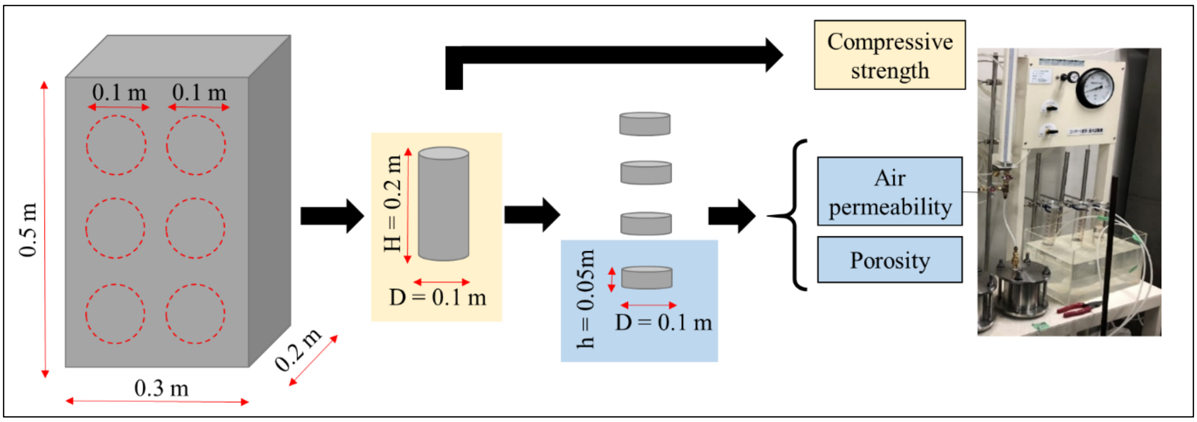


Figure 2. Flow chart of the procedure to obtain specimens for the experimental tests for TSC and conventional concrete.

2.3 Casting procedures and experimental tests for mortar

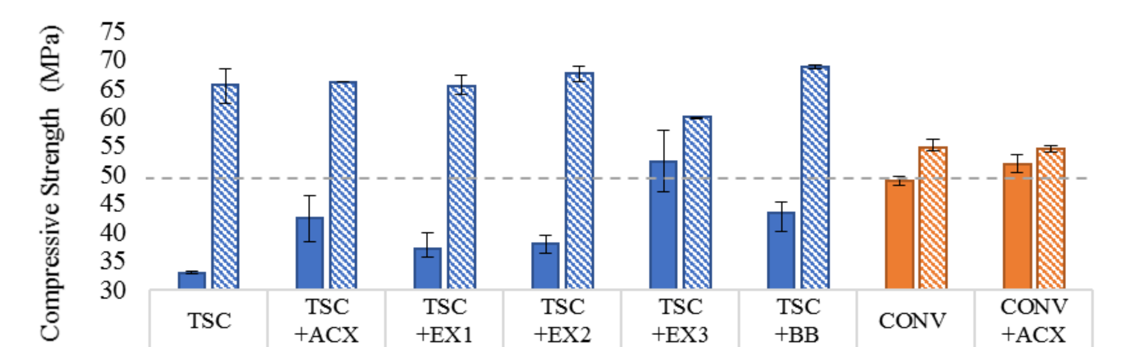
To verify if the improving methods were acting on the cement matrix or on the ITZ of TSC, mortar specimens were also produced, with the same composition of the mixtures in Table 3, but without coarse aggregate. It should be noted that the identification "TSC" for mortar test results refers to the industrialized grout, used as a binder in the TSC, while the identification "CONV" relates to mortar produced with OPC with 40% GGBFS replacement.

The mortar cylindrical specimens with diameter D = 0.05 m and height h = 0.1 m were cured in water for 28 days. Axial compressive test was performed adapting JIS A 1108:2018 for the specimens' size, and the porosity was determined according the procedures described in 2.2.3, but using the fragments obtained from the compressive test.

3. RESULTS AND DISCUSSIONS

The compressive strength test results for concrete (TSC and conventional) and mortar are shown in Figure 3. The use of ACX in the concrete mixtures improved the mechanical resistance of TSC (TSC+ACX) and conventional concrete (CONV+ACX). However, the strength's increase for TSC was higher (+29%), compared to the increase occurred in conventional concrete (+6%). This is caused by the action of the C-S-H nanoparticles in ACX, which can not only reduce the setting time but also fill the voids in the mortar and the ITZ of TSC, improving adhesion between coarse aggregate and cementitious material (Sakai et al., 2021). When comparing the effect of adding the expansive admixtures EX1, EX2, EX3, and the cement slag BB in concrete, it was observed that, in all cases, there was an increase of the compressive strength, but the CaO admixture (EX3) resulted in the most significant improvement (+59%) and even exceeded the strength of conventional concrete (CONV).

A different pattern can be seen in the mortar compressive strength results. It can be observed that there was no significant increase in the mechanical performance of mortars with the use of improving agents. This indicates that the admixtures acted in the ITZ of TSC and not only in the cement matrix of the mortar. Although mortars showed good mechanical strength, around 60 MPa, when they were used to produce TSC, it was not possible to reach similar values of strength for TSC, because the adhesion of the mortar to the coarse aggregate was the limiting factor, reducing the mechanical performance of TSC. It can be noted that EX3, despite resulting in lower compressive strength for mortar, resulted in the highest values for the TSC. As explained by Najjar, Soliman and Nehdi (2014), this is caused by the confinement effect induced by the interlocked aggregate particles in TSC, which limit the expansion of the mortar.



	TSC	TSC +ACX	TSC +EX1	TSC +EX2	TSC +EX3	TSC +BB	CONV	CONV +ACX
Concrete	32.9	42.5	37.0	38.0	52.3	43.3	48.8	51.9
Mortar	65.5	66.1	65.5	67.7	60.0	68.7	54.7	54.4

Figure 3. Compressive strength results for concrete (TSC and conventional) and mortar.

Figure 4 presents the results of concrete porosity and air permeability tests, and there is a linear relationship between these parameters for TSC. Also, the use of the improvement methods resulted in a reduction of the porosity to lower values, and of the air permeability coefficient to similar values compared to conventional concrete. However, for conventional concrete, there was no notable change in these parameters with the use of the ACX admixture. The reduction in the porosity and air permeability with the use of ACX for TSC confirms the effectiveness of ACX in reducing the ITZ, the weak point of TSC. In the case of conventional concrete there was no substantial improvement in these parameters because, although ITZ exists, its influence on concrete's performance is less significant than in TSC.

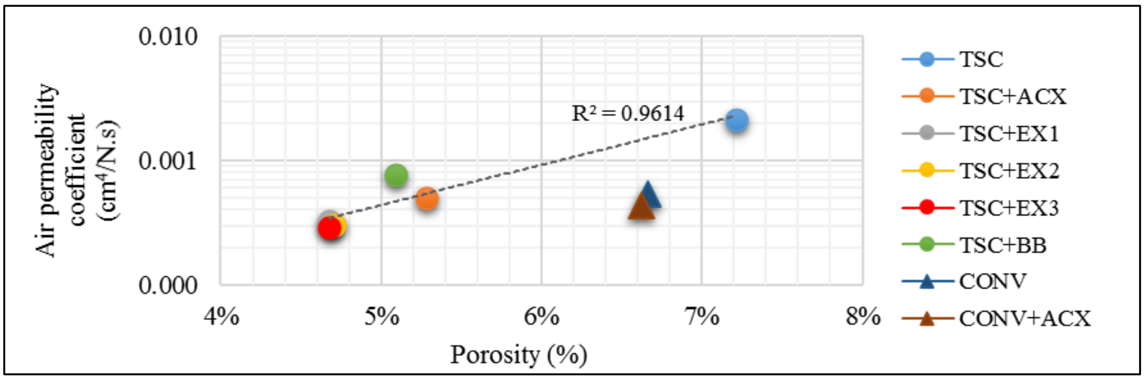


Figure 4. Relationship between porosity and air permeability coefficient for TSC and conventional concrete.

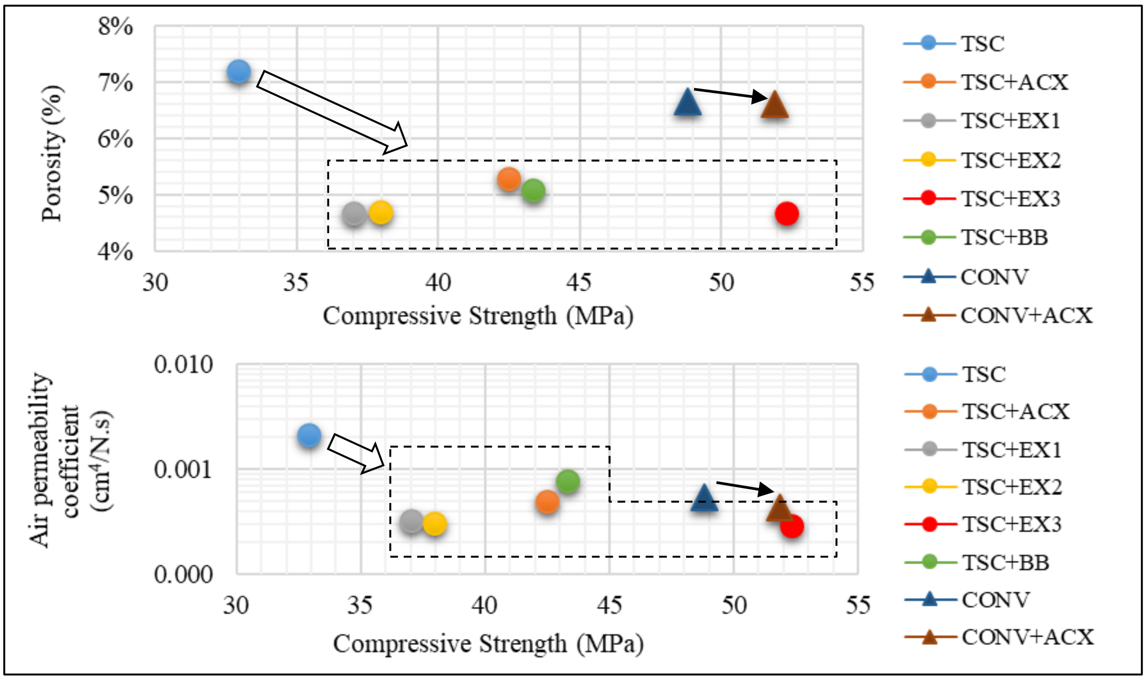


Figure 5. Relationship between porosity and compressive strength and air permeability coefficient and compressive strength for TSC and conventional concrete.

Figure 5 relates porosity and air permeability to the compressive strength results. Using different types of admixtures improved mass transfer properties of TSC to similar values, so the porosity and air permeability coefficient of TSC were similar for all improving methods. But the Figure shows that compressive strength was not the same, as previously shown in Figure 3, and only EX3 resulted in a significant increase in mechanical performance, to a value higher than conventional concrete. This confirms that the compressive strength of TSC is influenced, not only by the total porosity itself, but also by other parameters that affects the confinement caused by the expansive admixtures, such as compactness, position, and geometry of coarse aggregate.

To analyze which type of porosity was being improved, the porosity results of concrete and mortar were compared. In the Figure 6, it is possible to observe that all improving methods reduced the porosity of TSC, but for mortar, only EX3 and BB resulted in a significant reduction in the porosity of the cementitious matrix. Relating it to the compressive strength results (Figure 3), it is possible to affirm that the increase in mechanical strength of TSC with the use of EX3, BB and ACX, the last ones in a smaller rate, is also related to the reduction of cement matrix porosity, a result that was not obtained with the other admixtures (EX1, and EX2).

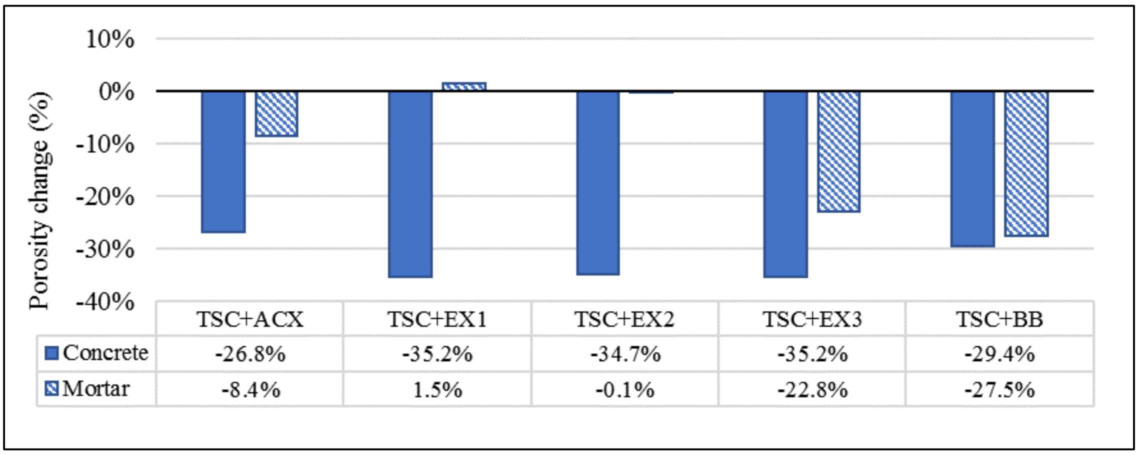


Figure 6. Porosity changes for TSC and mortar caused by the improvement methods.

The admixtures acted in different ways when improving the TSC performance, as summarized in the Table 4. Experimental results indicated that the use of CaO expansive admixture (EX3) acted in reducing the voids both in the cement matrix and in the ITZ and it was more effective than the addition of slag cement (BB).

Table 4. Effect of the adopted improvement methods for TSC

Admixture		**Cement matrix**	**ITZ**
1	**ACX**	△	○
2	**EX1**	×	○
3	**EX2**	×	○
4	**EX3**	○	◎
5	**BB**	○	○

Figure 7 illustrates the stress transfer and rupture models of TSC, elaborated after this experimental investigation. To achieve maximum performance, three main aspects need to be evaluated: (i) ITZ, (ii) strength and good particle size distribution of the aggregate and (iii) strength of the cementitious matrix itself. The last one usually is not the limiting factor for mechanical performance, as it is easier to ensure superior quality. If all these aspects are not secured, the rupture will occur (a) on ITZ or (b) on the aggregate, with lower resistance and without reaching the full capacity resistance of the cement matrix. If all factors are evaluated and combined, TSC can achieve its full performance and stress transfer will occur uniformly through cement matrix and aggregates (c). Since the geometric factor and good particle size combination for coarse aggregate were not evaluated in this study, it is believed that it is possible to achieve even better performance for TSC.

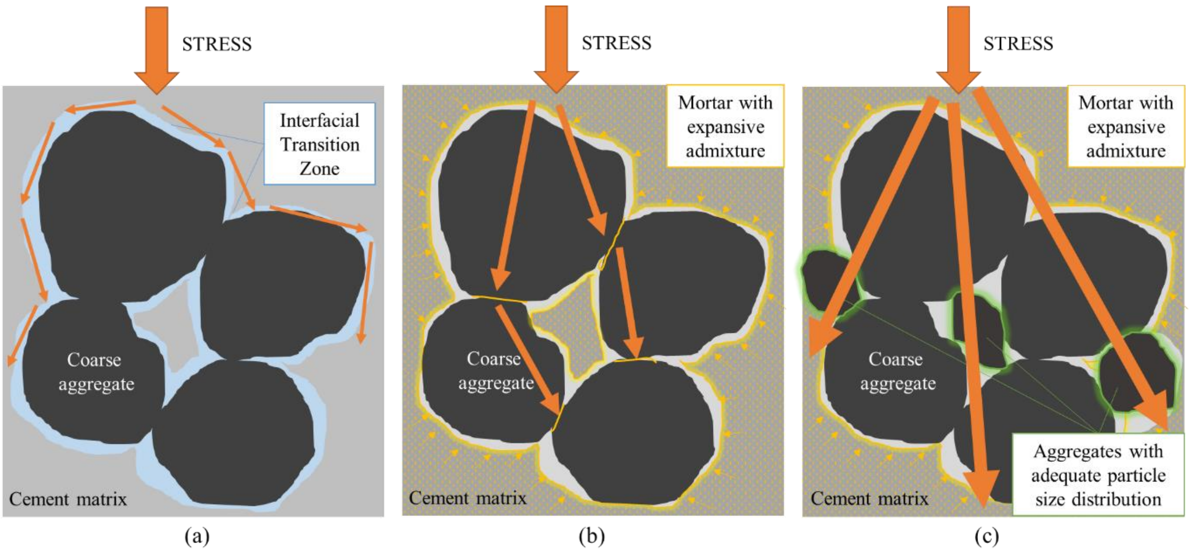


Figure 7. Rupture models for TSC: (a) on interfacial transition zone; (b) in the coarse aggregate; (b) in both cement matrix and coarse aggregate uniformly.

4. CONCLUSION

Two-Stage Concrete (TSC) has a peculiar mechanism of stress transfer, which may result in lower performance than conventional concrete, especially when high flow mortar is poured without injection. However, with the use of appropriate materials and good execution, the TSC without injection can achieve performance equal to or even better than conventional concrete, both in mechanical strength and mass transfer resistance, which is related to the durability of the hardened concrete.

To improve the performance of TSC without injection, several methods were evaluated in this research. The improvement methods contributed significantly to reduce the negative effect of the interfacial transition zone, which is one of the weak points of TSC. The use of C-S-H type hardening accelerator admixture (ACX) contributed to increase the compressive strength and air permeability resistance. Depending on the type of expansive material, the effect on the final properties of the TSC was different. While the addition of slag cement (BB) and CaO type expansive admixture (EX3) showed a positive influence on both mechanical and durability properties, ettringite (EX1) and mixed compound (EX2) based expansive admixtures reduced only the porosity and air permeability coefficient of the TSC, but did not improve compressive strength to the same extent.

Better performance and the consequent feasibility of TSC without injection for structural applications can be achieved with appropriate aggregate volume, geometrical shape and grading combination. Therefore, further research about these topics should be developed.

REFERENCES

Abdelgader, H.S. et al. (2015) ‘Self-Compacting Grout to Produce Two-Stage Concrete’. ISBS: 2nd International Sustainable Buildings Symposium, Ankara, Turkey, 28-30 May 2015.

An, X. et al. (2014) ‘Rock-filled concrete, the new norm of SCC in hydraulic engineering in China’, *Cement & Concrete Composites*, 54, pp. 89-99.

Esmaeili, M. and Amiri, H. (2022) ‘Laboratory Investigation into the Flexural Behavior of Embedded Concrete Sleepers in Two-Stage Concrete with Preplaced Ballast Aggregate’, *International Journal of Concrete Structures and Materials*, 16 (12).

JIS (2018) JIS A 1108:2018: Method of test for compressive strength of concrete.

JIS (2017) JIS A 6202:2017: Expansive additive for concrete.

JIS (2021) JIS A 6204:2021: Chemical admixtures for concrete.

Lee, S. et al. (2018) ‘Effects of Redispersible Polymer Powder on Mechanical and Durability Properties of Preplaced Aggregate Concrete with Recycled Railway Ballast’, *International Journal of Concrete Structures and Materials*, 12 (69).

Li, P.P. et al. (2019) ‘Conceptual design and performance evaluation of two-stage ultra-low binder ultra-high performance concrete’. *Cement and Concrete Research*, 125.

Najjar, M.F., Soliman, A.M. and Nehdi, M.L. (2014) ‘Critical overview of two-stage concrete: Properties and applications’, *Construction and Building Materials*, 62, pp. 47-58.

Najjar, M.F., Soliman, A.M. and Nehdi, M.L. (2016) ‘Two-stage concrete made with single, binary and ternary binders’. *Materials and Structures*, 49, pp. 317–327.

RILEM (1999) TC 116-PCD: Permeability of concrete as a criterion of its durability. *Materials and Structure*, 32, pp.163 -173.

Sakai, K. et al. (2021) ‘Study of Improving Performance of Recycled Coarse Aggregate Concrete by Several Methods for Pore Structure Modification’, *The 9th International Conference of Asian Concrete Federation (ACF2020/2021): Advanced & Innovative Concrete Technology*, Thailand, November 26–27, pp. 115-121.

Shibuya A., Iyoda T. (2019) ‘A Review of Preplaced-Aggregate Concrete Using Recycled Aggregate and Railway Wasted Ballast’, *16th East Asia-Pacific Conference on Structural Engineering & Construction (EASEC16),* Australia, December 3-6.

Yoon, J.Y. et al. (2015) ‘Lightweight Concrete Produced Using Two-Stage Casting Process’ Materials 2015, 8, pp.1384-1397.