

Effect of interlayer cold joint on mechanical properties and permeability of roller compacted concrete

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ABSTRACT One issue with layer application of roller compacted concrete (RCC) is the development of cold joints, which can cause damage to RCC structures. In this study, fly ash was used in place of 0%, 20%, 40%, and 60% of the cement or aggregate to examine the impact of interlayer cold joint formation on RCC mixtures. To promote cold joint formation, the second layer was placed and compacted with a delay of 0, 60, 120, or 180 min after the first layer. Three methods were tried for preventing cold joints from forming: one was to apply a bedding mortar to the interlayer, another was to add a set retarder admixture, and the third was to spray an adhesion-enhancing chemical additive on the surface of the first layer. Based on the 28 d specimens' compressive and splitting-tensile strengths as well as the depth of water penetration under pressure, the most effective method was found to be applying interlayer bedding mortar. Considering 180 min delayed layer castings, the splitting-tensile and compressive strengths of the control samples decreased by 31% and 17%, respectively, while the strengths of mixtures applying interlayer bedding mortar decreased by 9% and 10%. In addition, bedding mortar treatment decreased the water permeability by 59% compared to the control. Interlayer cold joint decreased all mixtures' moduli of elasticity, regardless of the age of the specimens. When the interlayer delay was 60 min, the modulus of elasticity decreased by 1%–4%. It was between 2% and 14%, and between 10% and 24% at 120 and 180 min for the interlayer delay. The longer the delay in placing the second RCC layer, the more detrimental the effect of the cold joint. This effect was most noticeable on mechanical and permeability properties tested with applied load or water pressure parallel to the cold joint, such as flexural and splitting tensile strengths and water penetration depth under pressure.

KEYWORDS roller compacted concrete, cold joint, mechanical properties, permeability properties, fly ash

1 Introduction

Roller compacted concrete (RCC) is a special type of concrete that has become increasingly popular in recent years due to its unique characteristics and benefits. Unlike traditional concrete, RCC is not poured and smoothed with a vibrating screed. Instead, it is placed with an asphalt paver or trucks and compacted with a vibratory roller. This results in a dense, durable concrete that can handle heavy loads and high traffic volumes. One

of the main benefits of RCC is its cost-effectiveness. Because it is easy to place and requires minimal finishing, it can be installed quickly and at a lower cost than traditional concrete. Additionally, RCC requires minimal maintenance and has a long service life, making it an ideal choice for high-traffic applications.

RCC is a preferred material for gravity dams, airport runways, and road pavements because of its cheapness, low heat of hydration, as well as fast and easy construction. In addition, RCCs have been widely used for years in various applications, such as timber warehouses, loading docks, port facilities and car parking [1].

RCC is made of materials that are comparable to those in conventional concrete. It is recognized, nevertheless, to have a larger aggregate content and a lower binder content than conventional concrete [2]. Part of the cement content in RCC can be replaced by a variety of mineral admixtures, including fly ash, slag, and silica fume. This replacement lowers production costs while simultaneously enhancing the concrete's mechanical, physical, and durability properties [3–7]. Concrete that is more economical and ecologically friendly can be made by reducing the amount of cement in the mixture. Since RCC dams are usually built in stages, the development of cold joints between layers cannot be prevented [8–12].

The phenomenon of cold joint is characterized by the weak bond formed between two concrete surfaces, which is often the result of the inability of the concrete layers to fully integrate with each other. As explained by Illangakoon et al. [13], the cold joints typically occur when the second layer of concrete is placed after the initial setting time of the first layer. However, there are instances when cold joint occurs even before the initial setting time, which can have a negative impact on the strength and durability performance of concrete structures as highlighted by Jatheeshan et al. [14]. It is important to note that the cold joints can lead to several challenges, including low shear strength and high permeability of RCC mixtures [15,16]. Consequently, seepage issues could occur with RCC dams, reducing their strength, durability, and structural integrity. As Sha et al. [17] pointed out, interlayers are crucial to ensuring the stability of RCC gravity dams. Therefore, in order to reduce the dangers related to cold joints and improve the general quality of concrete buildings, it is essential to carefully inspect and modify the interface between layers in RCCs. Weathering circumstances, mixture consistency, mix proportions, and the interval between layer castings all have an impact on the bond between the layers. The most significant characteristic among these contributing parameters is the interval between layer castings [18]. A summary of several relevant studies can be found below.

Karimpour [19] examined the time effect between production and compacting on the strength and permeability of RCC mixtures containing blast furnace slag (BFS). The specimens were prepared in 4 different periods of 30, 60, 120, and 180 min to determine the ideal time between production and compaction of RCC. It was observed that the properties of the mixtures containing no BFS were negatively affected with the rising of the time interval. However, the use of BFS as a part of cementitious materials improved the compressive strength and impermeability of RCC.

To find out how cold joint development between layers affected the tensile strength of RCC, Ribeiro et al. [20] conducted a study. The authors underlined that the tensile strength of RCC might be considerably reduced by the

cold joint, which develops when the next layer is not placed in a timely manner. To mitigate this negative effect, different methods were tested. For instance, applying only mortar between the layers was not found to be sufficient in increasing the tensile strength of RCC. Likewise, the application of coarse aggregate alone by removing the surface mortar did not yield satisfactory results. However, applying both methods together was found to be effective in reducing the negative effect of cold joints on the tensile strength of RCC.

According to a study by Mardani-Aghabaglou et al. [21], in samples produced without any delay between layers, the depth of water penetration in the direction perpendicular to the casting direction was larger than that parallel to the casting direction. The fact was attributed to the formation of cold joints between layers even when there was no delay in the casting of subsequent layers.

Li et al. [22] stated that the risk of seepage in dams was lower when RCC was applied in 2 layers rather than in three layers.

Aguiar et al. [23] looked into how the strength of RCC mixtures was affected by cold joint formation and fly ash replacing some of the cement. The researchers noticed that the compressive strength of RCC mixtures decreased with the addition of fly ash and an increase in its level of inclusion. This detrimental effect persisted even in the 365 d specimens, even though it became less pronounced with age. It's interesting to note that the study additionally found that interlayer cold joint formation was improved by the interval between layer placement and the rise in fly ash substitution level. Cold joint formation led to a drop in tensile strength that was larger than a reduction in shear strength. This can be attributed to the low surface roughness of the bottom layer, which resulted in weak interlayer bond.

In an investigation by Qian and Xu [24], the impact of interlayer delay times on the mechanical and permeability properties of RCC was examined. The researchers focused on looking at how the concrete specimens were affected by delays of 0, 3, 6, 9, 12, and 15 h. The findings demonstrated that while the concrete specimens' permeability rose, their splitting-tensile strength dropped as the delay interval increased.

Liu et al. [25] studied the impact of layer application delays on the shear strength of RCC mixtures and interlayer treatment methods. It was found that the mixtures' shear strength decreased as a result of the layers' delayed application. The negative impact become more noticeable as the application time interval between the layers increased. It emerged that casting the second layer prior to the first layer's initial setting period had no appreciable impact on the shear strength of RCC. However, the shear strength of RCC will noticeably decrease if the second layer is poured after the first layer's initial setting time but before the first layer's final

setting time. Furthermore, it is important to take into account that the time of the second layer's pour can have an impact on the tensile strength of RCC mixtures. The tensile strength of the RCC mixture will be negatively impacted if the second layer is applied after the first layer's ultimate setting time. To maintain the specimen's strength, it is advised to pour the second layer within the specified time frame. Three different methods (mortar, mortar + expanding chemical admixture, and mortar + nano SiO₂) were applied to reduce this negative effect. Among these methods, the applications of mortar + expanding admixture and mortar + nano SiO₂ between the layers were more successful than the only mortar application.

According to the literature, there are many studies related to the durability and mechanical performances of RCC mixtures. However, the impact of cold joints resulting from delayed layer application on the mechanical and durability properties of RCC mixes is not commonly known. The presence of cold joints in the concrete member is significantly adverse affected its permeability, strength and durability performances. Solving problems is important as it will prolong the service life of concrete. Some studies were carried out by researchers with the aim of eliminating the cold joint formation in the concrete members. However, it was understood that the mentioned problem was not fully resolved. In addition, high use of fly ash, which is ecologically and economically important, is possible in RCC mixtures.

The present research focused on the interlayer cold joints affected the permeability and mechanical properties of RCC containing fly ash. Three methods were used to prevent the formation of interlayer cold joints: an adhesion-enhancing admixture at the specimen's interlayer, a bedding mortar between layers, and the addition of a set-retarding admixture to RCC mixtures. RCCs' elastic modulus and Poisson ratios were ascertained, together with their flexural, splitting tensile and compressive strengths of 28 and 90 d. Furthermore, utilizing the water penetration depth under pressure tests, the permeability performance of RCCs was evaluated.

2 Materials and method

2.1 Materials

The materials used were CEM I 42.5 R type cement and F type fly ash that met EN 197-1 and EN 450-1 requirements, respectively. Tables 1 and 2 list the fly ash and cement's mechanical, physical, and chemical properties that were obtained from the manufacturer.

In the experimental study, crushed limestone aggregates in size fractions of 0–5, 5–12, and 12–22 mm were used. The water absorption capacity and saturated surface

dry (SSD) specific gravity of these aggregates, as detailed in Table 3, were measured following the EN 1097-6 standard, while sieve analysis was performed according to TS EN 933-1. The aggregate mixture comprised 60% of 0–5 mm, 20% of 5–12 mm, and 20% of 12–22 mm aggregates. The grading limits for this mixture are depicted in Fig. 1, showing that the grading curve of the combined aggregate falls within the limits specified by the TS 802 standard.

Table 4 outlines the characteristics of the set retarding admixture and the synthetic rubber-acrylic polymer-based adhesion enhancing admixture, both of which are utilized in the first and second methods to mitigate the impact of cold joints between RCC layers.

Table 1 Chemical properties of cement and fly ash

Oxide	Cement (%)	Fly ash (%)
SiO ₂	18.53	49.70
Al ₂ O ₃	5.01	17.01
Fe ₂ O ₃	2.74	8.87
CaO	63.51	10.88
MgO	1.06	5.95
Na ₂ O	0.40	1.66
K ₂ O	0.75	1.30
SO ₃	3.14	2.52

Table 2 Mechanical and physical properties of cement and fly ash

Property	Cement	Fly ash
Compressive strength (MPa)		
2 d	2.43	–
7 d	39.30	–
28 d	47.00	–
Strength activity index (%)		
7 d	–	81
28 d	–	87
Fineness		
blaine specific surface (cm ² /g)	3530	4300
residual on 32 μ sieve (%)	22.4	16.5
residual on 90 μ sieve (%)	1.0	5.3
Specific gravity	3.15	2.31

Table 3 Aggregate physical properties used in RCC

Type	Size (mm)	SSD bulk specific gravity	Loose bulk density (kg/m ³)	Water absorption capacity (%)
Crushed limestone	0–5	2.68	1655	1.64
	5–12	2.68	1441	0.51
	12–22	2.69	1405	0.40

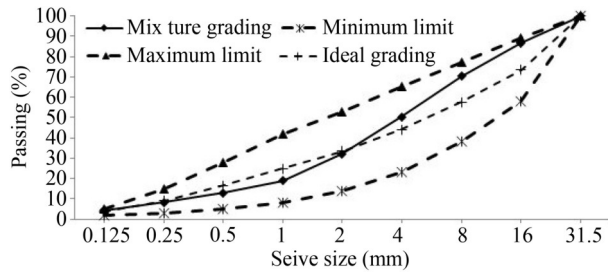


Fig. 1 Grading curve of mixed aggregates and maximum and minimum limits, ideal grading of TS 802.

Table 4 Properties of set retarding and adhesion enhancing admixtures

Type	Active ingredient	Density (kg/m ³)	pH	Solid content (%)
Set retarding	modified saccharide	1340–1400	5.50–9.50	70–74
Adhesion enhancing	synthetic rubber-acrylic polymer	1057	2.79	28.8

To enhance the workability of the mortar in the third method, a superplasticizer was incorporated into the bedding mortar mixtures. This allowed the mortar to be placed easily without the need for vibration. The properties of the superplasticizer are detailed in Table 5.

The superplasticizer and set retarding admixture were used as 0.8% and 0.4% by weight of cement, respectively. The adhesion enhancing admixture was sprayed on the surface of the specimens at a rate of 250 g/m².

2.2 Method

2.2.1 Determination of the mix proportions and water content

In this study, the maximum density method according to ACI 207.5R.99 Recommendation was used to design RCC mixtures. The cement dosage in the control mixture (C) was selected as 250 kg/m³. Different combinations were created in the first series (A series) using different cement substitutes. A1, A2, and A3 mixtures were produced by substituting fly ash for 20%, 40%, and 60% of the cement, respectively. Similar steps were taken in the second series (B series), but the aggregate was changed. Again, fly ash replaced 20%, 40%, and 60% of the aggregate (by cement weight), resulting in combinations designated B1, B2, and B3, in that order.

To find the ideal water content for best performance, RCC mixes with water/binder ratios (*W/B*) ranging from 0.30 to 0.55 were created. Next, the mixes were put into cylinder molds measuring 150 by 300 mm. This process was done in three distinct layers to facilitate even distribution. Each layer was subjected to a compaction process using a vibrating hammer, which was applied on a steel pressure plate for a duration of 20 s. This method of compaction was performed in accordance with ASTM C1435 standards, as clearly illustrated in Fig. 2.

The water content and dry unit weight were determined

using the wet and oven-dry weights of the mixtures, with calculation details provided in a separate source [26]. Figure 3 illustrates the relationship between dry unit weight and water content for the mixtures. From the resulting curves for each mixture, the optimal water content, which corresponded to the maximum dry unit weight, was determined. The RCC *W/B* ratio was then computed using these values.

Table 6 shows the binders' composition, the mixtures' maximum dry unit weights, and their ideal water content.

The optimum water content of RCC mixtures rose with higher levels of fly ash substitution. This rise in fly ash content resulted in an increase in the proportion of fine materials in the mixture, thereby increasing the water requirement and optimum water content. Additionally, because the specific gravity of cement and aggregates is higher than that of fly ash, the maximum dry unit weight of the mixture decreased as the fly ash content increased. Table 7 provides the proportions of the seven most suitable mixtures concerning optimum water content.

Table 5 Properties of superplasticizer used in bedding mortar mixtures

Property	Polycarboxylate ether-based (liquid)
Chloride content (%)	< 0.1
pH value	5–8
Density (g/cm ³)	1.023–1.063
Alkali content Na ₂ O (%)	< 10



Fig. 2 Vibrating hammer, steel plate, additional ring, and cylinder mold used to produce RCC specimens.

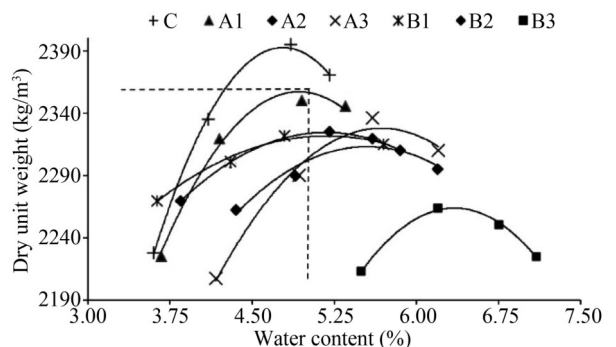


Fig. 3 Relationship between maximum dry unit weight and optimum water content of RCC mixtures.

Table 6 Binder ratio, optimum water content and maximum dry unit weight of the mixtures

Mixture	Binder composition	Maximum dry unit weight (kg/m ³)	Optimum water content (%)
C	100 cement	2384	4.85
A1*	80 cement + 20 fly ash	2358	4.90
A2	60 cement + 40 fly ash	2325	5.13
A3	40 cement + 60 fly ash	2330	5.60
B1*	100 cement + 20 fly ash	2322	5.10
B2	100 cement + 40 fly ash	2316	5.50
B3	100 cement + 60 fly ash	2264	6.65

*Note: In A series, replaced certain proportions of cement with fly ash and in B series, replaced certain proportions of aggregate with fly ash.

Table 7 Mixture proportions required to produce 1 m³ of RCC (kg/m³)

Mixtures	Cement (kg)	Fly ash (kg)	SSD aggregate (kg)			Water (kg)	Water/Binder	Theoretical unit weight (kg/m ³)	Fresh unit weight (kg/m ³)
			0–5 mm	5–12 mm	12–22 mm				
C	250	0	1308	436	438	120	0.48	2432	2500
A1	200	50	1294	431	433	122	0.49	2408	2477
A2	150	100	1281	427	429	123	0.49	2387	2448
A3	100	150	1252	417	419	126	0.50	2338	2460
B1	250	50	1232	411	412	133	0.44	2488	2496
B2	250	100	1158	386	388	138	0.39	2420	2448
B3	250	150	1058	353	354	145	0.36	2310	2412

2.2.2 Investigating the cold joint between roller compacted concrete layers

To investigate the effects of time-dependent interlayer cold joints in RCC mixtures, two layers of 150 mm cubic specimens were produced. The first layer was cast and compacted, while the casting and compacting of the second layer were put off for 0, 60, 120, and 180 min. Additionally, three different techniques were adopted to avoid the onset of interlayer cold joints: 1) a set retarding admixture was added to the RCC mixtures to delay concrete setting; 2) a 1 cm thick bedding mortar layer was applied to the top surface of the first layer before placing the second layer; 3) a synthetic rubber-acrylic polymer-based adhesion enhancing admixture was sprayed on the surface of the first layer before placing the second layer.

It is well-known that the glue must be stronger than the pasted material for a proper bond [27]. In this context, the mortar mixture, possessing a compressive strength of 66 MPa (at 28 d), was produced according to ASTM C109 by using crushed limestone sand conforming to ASTM C33. The superplasticizer was added to provide the desired consistency ((180 ± 20) mm for slump-flow) of the mortar mixture. Mix proportions of the bedding mortar are tabulated in Table 8.

The splitting tensile strength, compressive strength and water penetration depth under pressure tests were conducted on the 28 d control specimens in order to determine the effect of these three distinct methods on the interlayer cold joint. Detailed analysis of the test results

Table 8 Slump-flow and mixture proportions of bedding mortar

Materials	Amount (g)
Water	242.5
Cement	500
Superplasticizer	4
Sand	1350

revealed the most effective method among the three. Consequently, using the selected method for inhibiting cold joints, comprehensive 28 and 90 d tests were performed. These tests included not only compressive strength and splitting-tensile strength but also flexural strength and elastic modulus. The extensive testing was carried out on the control specimens as well as the specimens from series A and B, all of which were produced using the method identified as the most effective in mitigating the cold joint issue.

3 Test methods

The splitting-tensile, compressive and water penetration depth under pressure tests of RCC mixtures were performed on 150 mm cube specimens in accordance with EN 12390-6, EN 12390-3, and EN 12390-8 standards, respectively. The load or water pressure was applied parallel to the cold joint in these tests. Additionally, prismatic beam specimens of 100 mm by 100 mm by 600 mm were subjected to four-point flexural

testing in compliance with EN 12390-5 (Fig. 4(a)). In compliance with ASTM C469, cylinder specimens measuring 150 mm by 300 mm underwent testing for modulus of elasticity and Poisson's ratio (Fig. 4(b)). It is clear from these tests that the applied load was not parallel to the cold joint. The average of three specimens is used to report the values.

In addition, 150 mm cube specimens were prepared in 2 layers, Ø150, 300 mm cylinder specimens in 3 layers and 100 mm × 100 mm × 600 mm prismatic beam specimens in 2 layers. The placement of cube and prismatic specimens in the molds is shown in Figs. 5 and 6.

4 Results and discussion

4.1 Examination of interlayer treatment methods

Figures 7 and 8 display the 28 d splitting-tensile and compressive strengths as well as the water penetration depths under pressure of the control RCC specimens produced with different cold joint inhibiting techniques. C, CM, CR, and CA refer to the control specimens without any interlayer treatment, mortar-treated specimens, set retarding admixture-bearing specimens and adhesion enhancing admixture-treated specimens, respectively.

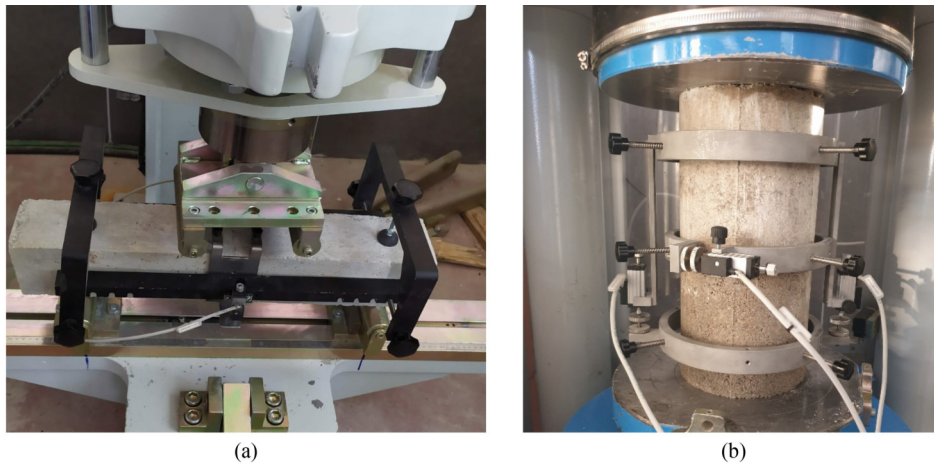


Fig. 4 (a) Four-point flexural; (b) elastic modulus tests.



Fig. 5 Placement of prismatic specimens in molds.



Fig. 6 Placement of cube specimens in molds.

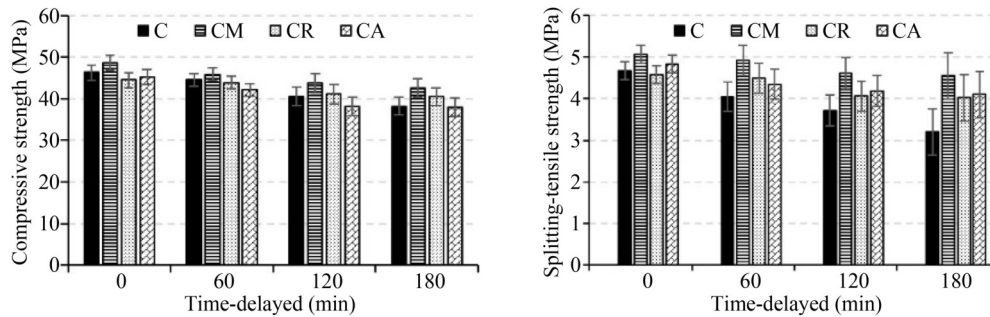


Fig. 7 (a) 28 d splitting-tensile and (b) 28 d compressive strengths of samples produced with various interlayer treatment techniques.

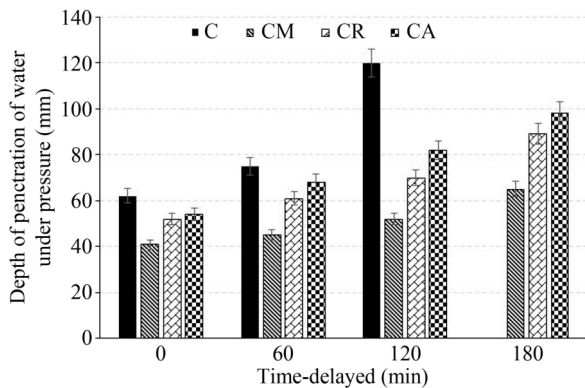


Fig. 8 Water penetration depth under pressure of 28 d RCC samples produced with various interlayer treatment techniques.

Comparing the compressive strengths of the specimens placed in the second layer without delay and with 180 min delay, the strength of the C specimens decreased by 17%, while the corresponding values were 12%, 9%, and 16% for CM, CR, and CA specimens, respectively.

The splitting-tensile strength loss of the C samples whose second layer was applied after 180 min was 31%, while the strength loss of CM, CR, and CA specimens was 10%, 12%, and 15%, respectively.

The C specimens, in which the second layer was applied 180 min later without any interlayer treatment showed no resistance to the water penetration under pressure. However, compared to those of the corresponding control specimens (0 min delay), the depth of water penetration of CM, CR, and CA specimens decreased by 59%, 71%, and 81%, respectively. Test results revealed that although cold joint treating methods reduced the permeability of RCC specimens to some extent, nevertheless, none of the methods was fully successful in preventing water penetration under pressure. Moreover, the increase in permeability became noticeable with a longer delay period between the layers.

It was determined that the most proficient way to avert the undesirable results of the cold joint is to apply a mortar layer in between the concrete layers, taking into account the splitting-tensile strength, compressive strength and water penetration depth under pressure of the RCC mixtures. The application of mortar is thought to

create this positive effect by increasing both surface roughness and adherence between the layers. According to He et al.'s study [28], the mechanical interlocking and bond strength between layers rose as the surface roughness at the interface between newly poured and old concrete grew. Thus, it was stated that the mechanical properties of concrete improved [28,29].

Application of the adhesion enhancing admixture between layers is the method with the lowest positive effect among other methods. The negative effects of the cold joint on the mechanical and permeability properties were slightly reduced compare to the control mixture. Similar to this, an epoxy-resin-based bonding agent was employed between layers in the Santos et al. investigation [30]. The test findings showed that using a bonding agent improved the specimens' bond strength in shear. They also stated that the use of this agent can prevent adhesive failure.

According to He et al. [28], air bubbles and microcracks that form at the interlayer have a detrimental effect on the permeability and strength of concrete. It is indicated that polymer-based adhesion enhancing admixture contributes to the mechanical interlocking by reducing the bubbles interlayer. In addition, these admixtures are thought to increase the adherence between the layers by covering the surface of aggregate and cement particles. Thus, micro-crack formation can be prevented [31,32].

The fracture toughness and energy of RCC interlayers were examined by Luo et al. [33], who additionally examined at different interlayer treatments and time intervals. The important effects of interface treatment and deployment delay on RCC interface fracture performance were emphasized. Reduced fracture energies were linked to longer layer placement delays. The qualities of interlayer fracture were improved by adding cement mortar and interlayer roughening. Techniques like green cutting or groove cutting for surface roughening notably augmented interlocking between aggregates in upper and lower RCC layers, correlating positively with surface roughness and thereby enhancing fracture toughness and energy.

Shen et al. [34] investigated the shear properties of RCCs by making treatments with different methods such

as cementitious system and surface roughness applications between RCC layers. The test findings showed that greater surface roughness between the layers improved the bonding between the layers and enhanced the strength of shear. In addition, cementitious system application improved the cohesion, shear strength and friction angle of RCC layers. Among the interlayer mortar and cement paste applications, mortar application provided significant improvements. Similar to this study, the application of bedding mortar between the layers improved the concrete's adhesion, which had a favorable impact on the RCCs' permeability, flexural strength, and compressive strength.

Maier and Lees [35] studied the fracture properties of layered concrete mixtures, focusing on the effects of delayed pouring up to 4 h. It was found that delayed casting led to a decrease in splitting strength due to cold joint, particularly in high-strength concretes. The critical delayed casting time was found to be lower in high-strength concretes than in low-strength concretes. Gungor et al. [36] stated the importance of casting the second layer within one hour to ensure sufficient bond strength with the first layer. They further emphasized the necessity of implementing treatment processes to achieve the desired bond strength in the layer castings within the aforementioned timeframe. Similar findings were obtained in this investigation, showing that the cold joint effect reduced the strengths of RCCs with delayed layers independent of the effectiveness of the treatment approaches. It was established that 60 min was the key delay time. Three techniques were used to lessen the bad effects of the cold joint.

In this section, it was determined that the most effective method is the application of bedding mortar between layers. In Subsections 4.2 and 4.3, the 28 and 90 d mechanical properties and permeability of interlayer bedding mortar-bearing specimens containing fly ash were compared with those of the A and B series specimens without the bedding mortar.

4.2 Mechanical properties of rcc mixtures with mortar applied between layers

4.2.1 Strength

The 28 and 90 d compressive strength, splitting-tensile strength, and flexural strength test results of mixtures from various series, specifically the C, A series, B series, CM, AM series, and BM series, are presented in Tables 9, 10 and 11, respectively.

The 90 d strengths of RCC mixtures were higher than the 28 d strengths mainly due to the continuation of the cement hydration process and the pozzolanic reaction of fly ash in all the series [37]. This is because, the cement hydration process continues even after 28 d, resulting in higher strength at 90 d. In "A" series mixtures, where a

Table 9 Compressive strength of mixtures (MPa)

Mixtures	0 min delay		60 min delay		120 min delay		180 min delay	
	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	46.3	58.6	44.5	55.7	40.6	49.6	38.3	47.4
A1	41.7	50.1	41.4	52.0	36.2	44.2	31.5	39.7
A2	34.5	44.2	32.7	41.3	30.2	39.2	29.4	36.1
A3	29.1	38.5	24.8	36.2	22.4	30.6	20.8	26.9
B1	49.5	62.1	48.3	60.3	43.6	52.4	41.3	49.3
B2	52.0	64.1	50.6	61.2	44.1	54.7	42.4	50.1
B3	53.6	66.4	51.0	65.5	45.3	54.9	41.2	51.4
CM	48.7	57.3	45.9	54.9	43.8	51.4	42.6	48.1
A1M	42.4	51.4	42.1	52.7	39.5	46.3	38.1	44.4
A2M	36.2	45.9	34.1	43.6	32.5	40.2	31.4	38.7
A3M	27.4	37.4	27.6	35.5	26.3	33.5	23.6	29.1
B1M	51.3	64.1	48.4	61.5	46.6	54.7	45.3	52.6
B2M	53.0	65.2	47.7	62.9	47.9	56.1	46.9	55.1
B3M	53.1	68.7	48.3	66.1	46.5	55.0	43.9	56.3

Table 10 Splitting-tensile strength of mixtures (MPa)

Mixtures	0 min delay		60 min delay		120 min delay		180 min delay	
	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	4.70	5.00	4.10	4.40	3.70	3.90	3.20	3.40
A1	4.60	4.80	3.80	4.10	3.70	3.80	3.00	3.30
A2	3.50	3.70	3.40	3.70	3.20	3.60	3.10	3.30
A3	3.20	3.50	3.20	3.50	2.80	3.10	2.60	2.90
B1	4.70	4.70	4.50	4.50	3.80	4.20	3.50	3.90
B2	5.10	5.30	4.80	5.00	4.00	4.40	3.60	3.90
B3	5.00	5.40	4.20	5.10	4.10	4.60	3.30	4.10
CM	5.10	5.30	4.90	5.10	4.60	4.70	4.20	4.20
A1M	4.70	5.00	4.60	4.80	4.20	4.20	4.10	4.10
A2M	3.80	4.10	3.70	3.80	3.70	3.90	3.10	3.30
A3M	3.20	3.40	3.20	3.50	3.10	3.30	2.90	2.90
B1M	4.70	4.90	4.60	4.70	4.40	4.50	4.30	4.50
B3M	5.10	5.50	5.00	5.30	4.80	4.90	4.70	4.70

part of the cement content was replaced with fly ash, the strengths decreased compared to that of the control mix. On the other hand, the opposite happened and the strength rose in B-series mixtures when fly ash was added in place of some of the aggregate. This decrease in strengths of A series mixtures is attributed to their high W/B ratios as well as lower contribution of fly ash to the strength (than that of cement) even up to 90 d. However, the increase in the B series strengths is because of the contribution of the fly ash to the workability and strength as well as low W/B ratio of these mixtures [26]. The reduction in strength of RCC mixtures up on partial replacement of cement with fly ash was also reported by other investigators [38,39]. Furthermore, specimens with interlayer bedding mortar

Table 11 Flexural strength of mixtures (MPa)

Mixtures	0 min delay		60 min delay		120 min delay		180 min delay	
	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	5.05	5.57	4.14	5.21	3.25	4.28	3.20	3.95
A1	4.82	5.32	4.23	5.24	3.17	4.17	3.11	3.74
A2	4.68	4.94	4.09	4.81	3.14	4.05	3.02	3.52
A3	3.85	4.55	3.56	4.43	3.32	3.95	3.01	3.41
B1	5.14	5.71	4.03	5.45	3.35	4.51	3.32	3.97
B2	5.43	5.92	4.28	5.67	3.31	4.68	3.29	4.06
B3	5.48	6.14	4.82	5.96	3.73	4.87	3.11	4.15
CM	5.24	5.75	5.20	5.54	4.06	5.17	3.94	4.75
A1M	4.91	5.62	4.71	5.41	4.21	5.09	3.87	4.71
A2M	4.72	5.24	4.53	5.16	4.15	4.95	3.92	4.48
A3M	4.19	4.86	3.73	4.71	3.31	4.51	3.14	4.02
B1M	5.20	5.77	4.67	5.69	4.23	5.32	3.95	4.97
B2M	5.27	5.98	4.83	5.74	4.46	5.28	4.05	5.07
B3M	5.54	6.34	4.90	6.17	4.35	5.84	4.15	5.26

demonstrated marginally better flexural, compressive and splitting tensile strengths than mixtures without mortar. This improvement could be attributed to the additional layer of bedding mortar, which helps to increase the overall strength of the specimens. Furthermore,

increasing the delay period in placing of the second layer was found to weaken the interlayer further, thus, steadily decreasing the strength of the mixtures as the delay period increased. This indicates that the timely placement of the second layer of bedding mortar is crucial in order to obtain the desired strength properties of the mixtures.

To provide a comprehensive understanding of the effect of second layer placement delay on the strength of RCC specimens, the relative compressive, splitting-tensile, and flexural strengths of specimens with second layer delays of 60, 120, and 180 min were determined and presented in Figs. 9, 10, and 11, respectively. In this case, the specimens’ strengths in the second layer without any delay act as a benchmark for comparison. When the second layer was applied 60 min later, there was no discernible decrease in compressive strength in any of the specimens—B2M and B3M specimens excepted. In terms of splitting-tensile strength, the specimens containing the interlayer mortar showed good performance, while the negative effect of cold joint was noticeable in control (nontreated) specimens, except for A2, A3, B1, and B2 mixtures. From flexural strength viewpoint, except for A3, CM, A1M, and A2M specimens, there was a decrease in strength up to around 20%. As anticipated, the specimens whose second layer was applied 120 and 180 min later showed a greater loss in strength. Qian and Xu reported similar outcomes [24].

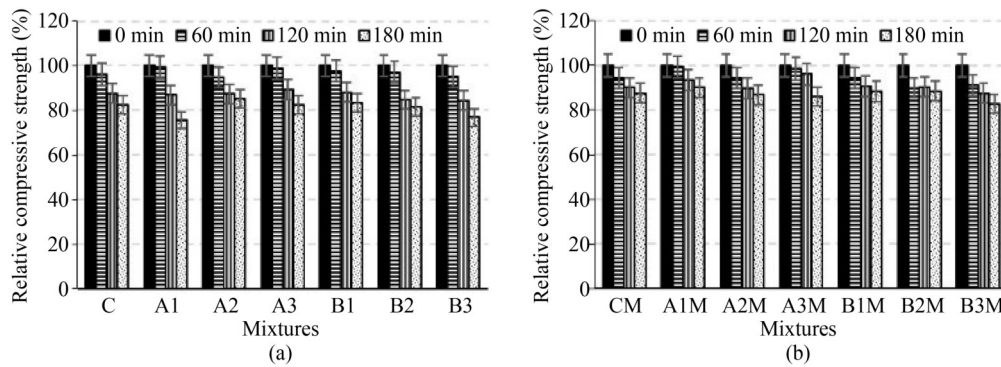


Fig. 9 Relative compressive strength of 28 d specimens with delayed second layer placement: (a) no interlayer treatment; (b) with interlayer bedding mortar.

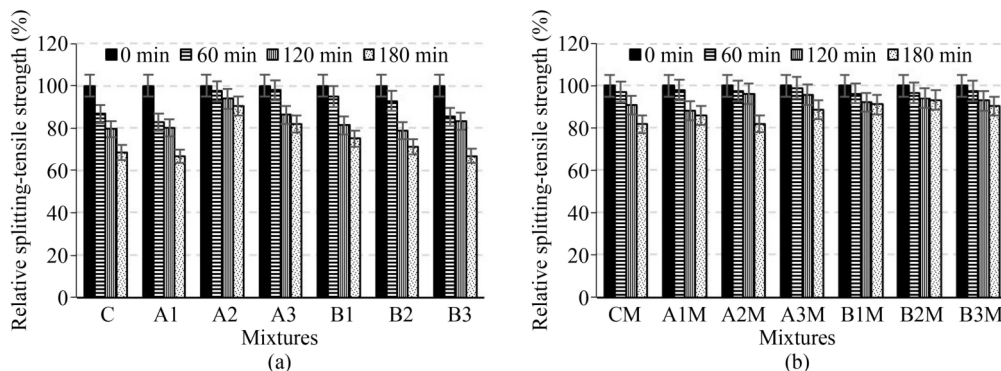


Fig. 10 Relative splitting-tensile strength of 28 d specimens with delayed second layer placement: (a) no interlayer treatment; (b) with interlayer bedding mortar.

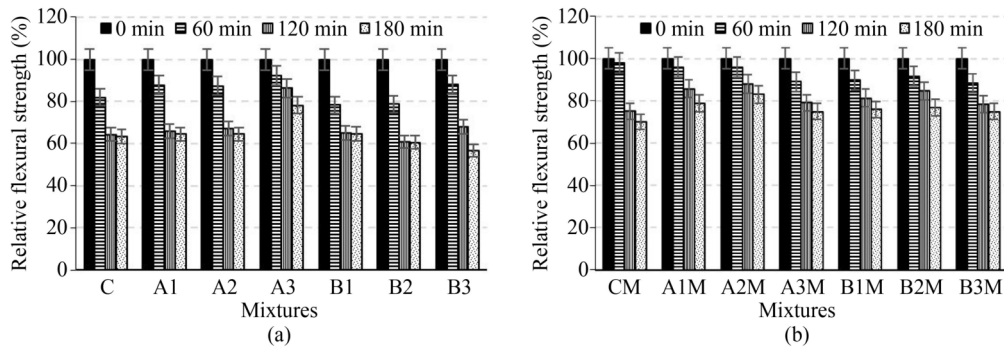


Fig. 11 Relative 28 d flexural strength: (a) no interlayer treatment; (b) with interlayer bedding mortar.

A delay of 180 min in placing the second layer led to a significant reduction in the compressive, splitting-tensile, and flexural strength of the specimens. Specifically, the reduction ranged from 15% to 24%, 10%–33%, and 22%–43%, respectively, for specimens without interlayer mortar. However, for mixtures containing mortar between the layers, the reduction was somewhat smaller, ranging from 10% to 17%, 7%–18%, and 17%–25%. These findings indicate that the use of interlayer mortar may help to mitigate the negative effects of delayed layer placement on strength. According to the reduction rates, it can be observed that the compressive strength of RCC was less affected by the presence of interlayer cold joints as compared to the flexural and splitting-tensile strengths. This indicates that the interlayer cold joint played a greater role in reducing the flexural and splitting-tensile strengths of RCC. However, the use of interlayer mortar proved to be more effective in maintaining the RCC's flexural and splitting-tensile strengths, as opposed to preserving its compressive strength. In addition, these rates decreased by increasing the curing time of the specimens to 90 d. The negative effect of interlayer cold joint on the strength decreased with both the use of interlayer mortar and prolonging the curing time.

The first layer of RCC loses its thixotropic behavior with C-S-H and other hydration products forming by elapsing time. This fact, when combined with the water evaporating off the concrete's surface, accelerates the process of surface hardening. Therefore, during casting of the second layer, it becomes difficult for aggregates to penetrate into the first layer. Thus, cold joint forms between the layers. Compared to the bulk mixture, in the vicinity of cold joint a greater amount of paste, hence, a lower amount of aggregate presents. The fact, accompanied with the smoothness of the first layer surface weakens the interlocking between the layers [20,23–25]. Figure 12 shows the views of RCC specimens after the compressive strength test, with the second layer placed at 0, 60, 120, and 180 min delay. The figure clearly demonstrates that a cold joint between the layers was inevitable with any delay in placing the second layer. The longer the delay, the more pronounced the effect

became. Consequently, a slight cold joint was formed in the specimens with a 60 min delay in placing the second layer, as shown in Fig. 12(b). This slight cold joint, while noticeable, did not significantly compromise the overall integrity of the specimen. However, when the delay period was extended to 180 min, the situation changed dramatically. The cold joint became very weak and fragile, resulting in a significant reduction in the specimen's structural strength. This weakness was so pronounced that the specimen split along the joint when subjected to compression, as clearly illustrated in Fig. 12(d). This demonstrates the critical importance of timely layer placement in maintaining the strength and integrity of the specimens.

The load–deflection diagrams plotted during the flexural test on the specimens without interlayer treatment and on the specimens with interlayer bedding mortar are shown in Fig. 13. As it was expected, RCC mixtures showed brittle fracture behavior under flexural loading, characterized by a sharp descending curve that is quite similar to the behavior observed in conventional concrete. Moreover, the midspan deflection values at the point of fracture were considerably lower for the RCC mixtures compared to those of the fiber-reinforced mixtures.

The crack development and failure cross-sections of RCC bending test specimens the second layer of which was placed with 180 min delay are shown in Fig. 14. The presence of interlayer cold joint (Fig. 14(a)) and its partial refinement by bedding mortar application (Fig. 14(b)) are obvious. Flexural crack development resulting in breaking the beam is shown in Fig. 14(c).

Figure 15 shows the correlations among the 28 d compressive, splitting-tensile, and flexural strength of the specimens. Regardless of whether interlayer mortar was present or not, there were robust linear correlations between compressive-flexural strengths and compressive-splitting tensile strengths. These relationships are very close to those of the conventional concrete.

4.2.2 Modulus of elasticity and Poisson ratio

The 28 and 90 d moduli of elasticity of specimens

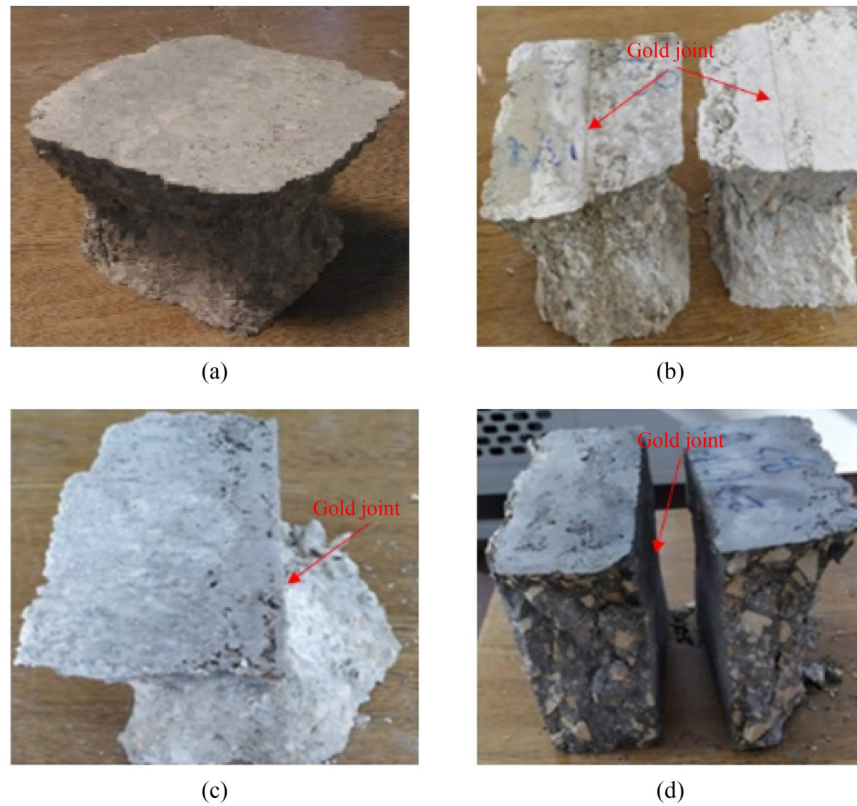


Fig. 12 RCC specimens after compressive strength test. Second layer was placed with: (a) 0 min delay; (b) 60 min delay; (c) 120 min delay; (d) 180 min delay.

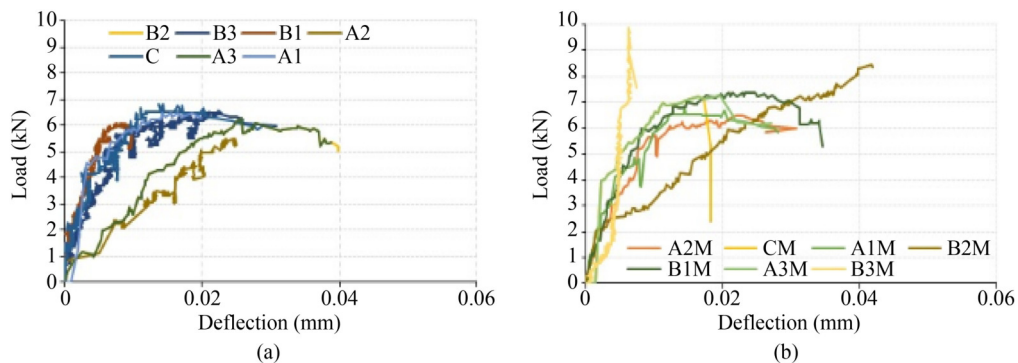


Fig. 13 Load-deflection diagram of specimens: (a) without interlayer treatment; (b) with interlayer bedding mortar.

without interlayer treatment and with interlayer mortar are shown in Table 12. Similar to the strength values, moduli of elasticity of mixtures improved by prolonged curing. However, the rate of increasing of elastic modulus was considerably lower than the rate of strength development within the same time interval. Replacing cement with fly ash led to decreased elasticity modulus, whereas substituting a portion of the aggregate with fly ash resulted in an increase in elasticity modulus. As the amount of fly ash increased, both effects became more prominent.

The deformations arisen from a given load increased by the presence of the cold joint and by increasing its intensity. Thus, the elastic modulus of the specimens

reduced further by delayed placing of the second layer. With the application of interlayer mortar, in the 28 d specimens the second layer of which was placed after 0 and 60 min, the modulus of elasticity increased by 1%–5% compared to specimens without mortar. On the other hand, specimens whose second layer was applied 120 or 180 min later showed an increase of 2%–19%. These levels were found to have dropped by 1% and 1%–11% in the 90 d specimens. In this context, applying interlayer mortar in RCC mixtures had not a considerable effect on the elastic modulus of the mixture and increased it slightly.

Taking the 28 and 90 d moduli of elasticity values obtained on specimens with no interlayer delay as the

baseline for comparison, the relative moduli of elasticity of concrete mixtures, both with and without interlayer mortar treatment, were calculated. The results of these calculations are comprehensively reported in Figs. 16 and 17. It was observed that, regardless of the age of the specimens, the presence of an interlayer cold joint invariably led to a reduction in the moduli of elasticity across all mixtures tested. Specifically, when the interlayer delay was 60 min, the reduction in modulus of elasticity was relatively modest, falling within the range of 1%–4%. However, as the interlayer delay increased, the impact became more pronounced. For an interlayer delay of 120 min, the reduction spanned a broader range, from 2% to 14%. The most significant reductions were

noted with an interlayer delay of 180 min, where the modulus of elasticity decreased substantially, ranging from 10% to 24%.

Regardless of the type of mixture and preparation method of specimens, the Poisson’s ratio of RCCs increased slightly with increasing the strength of the mix and varied between 0.14 and 0.18. These values are very close to those reported for the conventional concrete. In short, cold joint was found to have a negligible effect on the Poisson’s ratio of RCC.

4.3 Depth of water penetration under pressure

The depths of water penetration into the 28 and 90 d specimens with no interlayer treatment and with interlayer mortar are given in Table 13. Prolonging the curing period decreased the water penetration depth to some extent. This suggests that allowing the specimens to cure for a longer period enhances their resistance to water ingressing.

The study found that mixtures without interlayer mortar, specifically A2 and A3, showed no measurable resistance to water penetration when the second layer was casted with a delay of 120 min, and all mixtures that had a delay of 180 min also exhibited the same result. It became evident that the lack of interlayer mortar significantly compromised the water resistance of the specimens, resulting in deeper water penetration. However, the application of mortar interlayer significantly reduced the depth of water penetration. This indicates that the interlayer mortar plays a crucial role in creating a barrier against water ingress. It was also observed that mixtures with a higher W/B ratio, which included fly ash, had a greater depth of water penetration in the A series mixtures compared to mixtures without fly ash. This finding is consistent with similar studies conducted elsewhere [26].

The study discovered that applying interlayer mortar together with fly ash (series B mixes) in place of aggregate caused the specimens’ water penetration depth

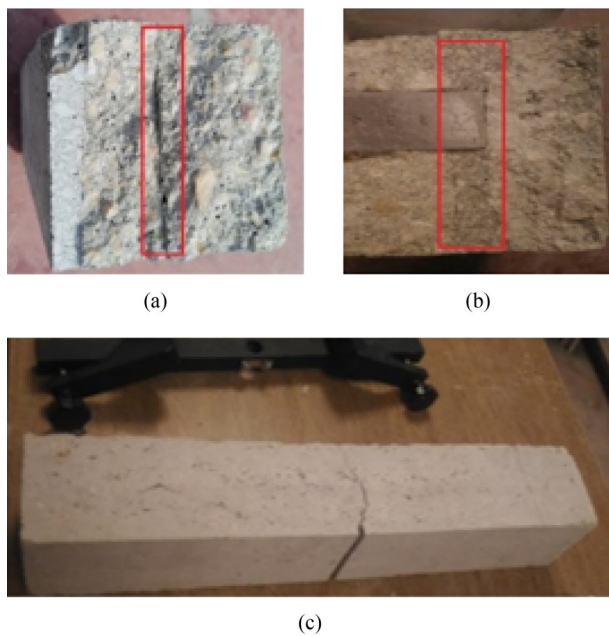


Fig. 14 View of beam specimens (second layer of which was placed with 180 min delay) after the flexural test: (a) failure cross-section of the specimen without interlayer treatment; (b) failure cross-section of the specimen with 1 cm thick interlayer mortar; (c) crack development after the flexural test.

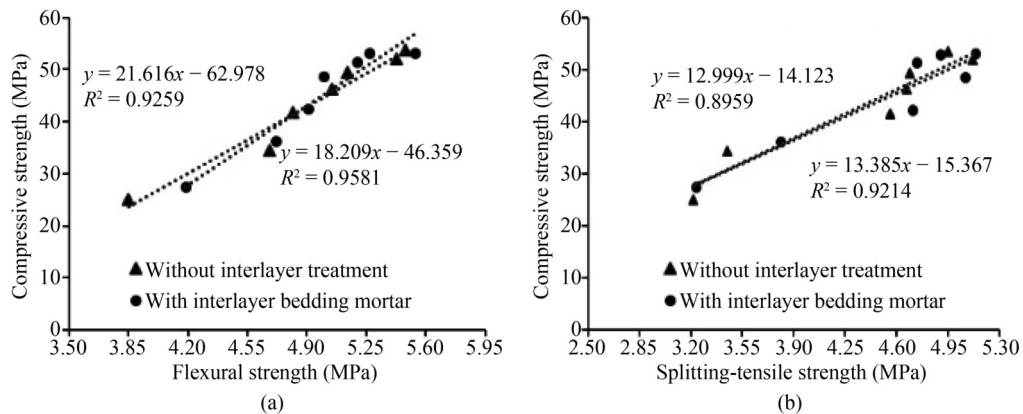


Fig. 15 Relation between: (a) compressive–flexural strengths; (b) compressive–splitting tensile strengths.

Table 12 Moduli of elasticity (MPa) obtained on 28 and 90 d RCC specimens

Mixture	0 min delay		60 min delay		120 min delay		180 min delay	
	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	32746	33925	32554	33127	30971	31115	26664	28274
A1	31281	32312	31152	31012	29102	30054	24236	27745
A2	28501	31256	27715	30751	26386	27241	21713	26451
A3	25372	28411	25042	28015	23125	24464	20527	21678
B1	33156	34759	32625	34786	30012	30879	25815	28254
B2	33516	35174	33137	34815	30872	31274	26274	28465
B3	33874	35571	33401	35243	31106	32957	27011	28764
CM	32849	33975	32815	33251	31548	31476	29683	30579
A1M	31285	32570	31146	31274	30429	31104	28110	28564
A2M	29531	31442	28845	30874	28155	29537	25814	26846
A3M	26309	28817	26187	28314	25903	26275	23006	23572
B1M	33635	35186	32894	34985	32372	33558	30108	31312
B2M	35019	35532	34124	35104	31514	32894	30354	31657
B3M	35105	35870	34925	35312	32116	33715	31849	32042

to decrease. The low *W/B* ratio and high paste concentration of these mixtures, which were proven to be helpful in strengthening the cold joint, were ascribed to this drop. The high paste content likely contributed to a

denser microstructure, providing better resistance to water penetration.

Taking the water penetration depth of the specimens prepared with no interlayer delay as the base of the comparison, the relative water penetration of the specimens was plotted in Fig. 18. The figure clearly shows that there is a positive correlation between the delay period and the permeability. Specifically, the longer the delay period, the higher the permeability. This suggests that delaying the casting process can negatively impact the water resistance of the concrete. On the other hand, the application of interlayer mortar was found to be highly effective in reducing permeability. This effect can be attributed to the enhanced interlocking and bond strength of the layers due to increased interlayer roughness [28,29]. Thus, it is thought that the permeability of concrete is reduced.

The effect of interlayer mortar on permeability appears to be more significant than its impact on mechanical properties. For example, in samples with no interlayer treatment and a second layer casted with a 180 min delay, water penetration test results could not be obtained due to the formation of a cold joint. Water has completely passed through the sample, indicating a significant compromise in permeability. However, in specimens that were treated with an interlayer, the increase in depth of water penetration was only in the range of 8% to 31%,

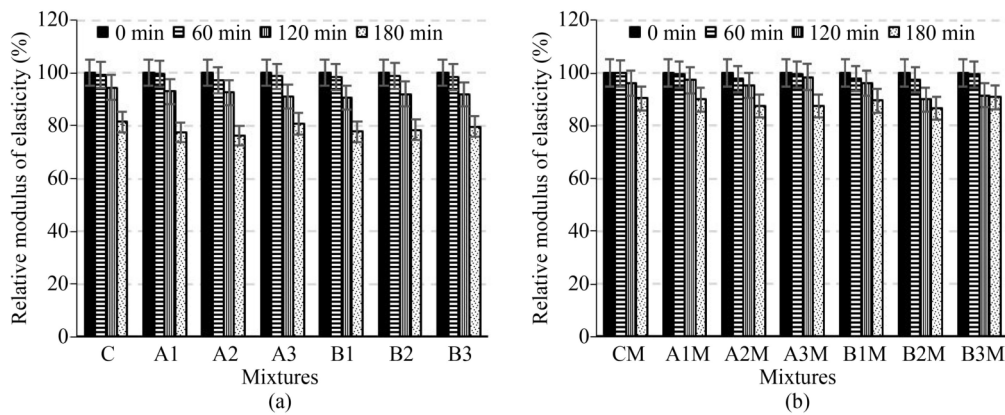


Fig. 16 Relative modulus of elasticity obtained on the 28 d specimens: (a) without interlayer treatment; (b) with interlayer mortar.

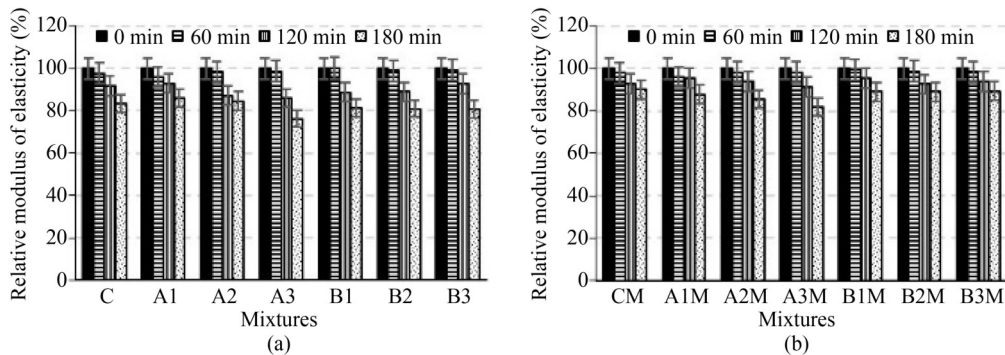


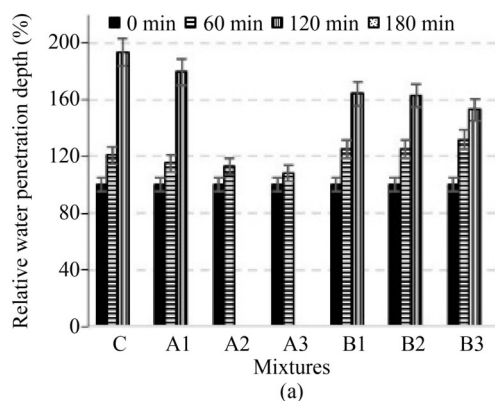
Fig. 17 Relative modulus of elasticity obtained on the 90 d specimens: (a) without interlayer treatment; (b) with interlayer mortar.

showing a marked improvement in resisting water ingress. It seems that the initial setting of the first layer occurred within 180 min, resulting in further weakening of the interlayer. This suggests that timing plays a crucial role in the overall integrity of the layered structure. Similar findings were reported by Qian and Xu [24].

Irrespective of the absence or presence of interlayer treatment, a strong linear relationship was found between the depth of water penetration and compressive strength, as depicted in Fig. 19. This relationship underscores the interconnected nature of mechanical properties and permeability, highlighting that even minor changes in the treatment process can have significant effects on the material's overall performance. Therefore, careful consideration must be given to the timing and application of interlayer treatments to optimize both permeability and mechanical strength in construction materials.

Table 13 Depth of water penetration into the specimens with and without interlayer mortar (mm)

Mixtures	0 min delay		60 min delay		120 min delay		180 min delay	
	28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
C	62	57	75	71	120	115	-	-
A1	73	70	84	80	131	124	-	-
A2	85	79	96	89	-	-	-	-
A3	99	94	107	102	-	-	-	-
B1	56	51	70	72	115	109	-	-
B2	52	47	65	58	106	102	-	-
B3	47	44	62	53	95	91	-	-
CM	41	35	45	42	52	49	68	65
A1M	49	44	56	51	57	54	71	68
A2M	62	55	59	54	64	62	69	67
A3M	67	61	72	68	78	75	86	85
B1M	40	34	44	41	48	44	55	51
B2M	36	32	39	35	45	41	51	48
B3M	32	27	35	32	38	36	46	42



5 Conclusions

The purpose of the described investigation was to ascertain how the mechanical characteristics and permeability of RCC are affected by interlayer cold joints. The cement and aggregate were partially substituted with fly ash. Various interlayer treatment methods were applied to eliminate cold joint effects on the characteristics of RCC. The following conclusions are made from the experimental data.

1) Among the three interlayer treatment techniques such as adding set retarding admixture to the RCC mixture, spraying adhesion enhancing admixture to the surface of first layer and applying a bedding mortar between the layers, the most successful one was the application of interlayer mortar. A 180 min delay in the application of layer castings resulted in a 17% reduction in the compressive strength and a 31% reduction in the splitting tensile strength of the control specimens. In contrast, the compressive and splitting tensile strengths of the mixtures that applied interlayer bedding mortar decreased by 9% and 10%, respectively. Furthermore, the bedding mortar treatment resulted in a 59% reduction in water permeability compared to the control.

2) By partially replacing cement with fly ash, the impermeability of concrete were reduced, as well as in

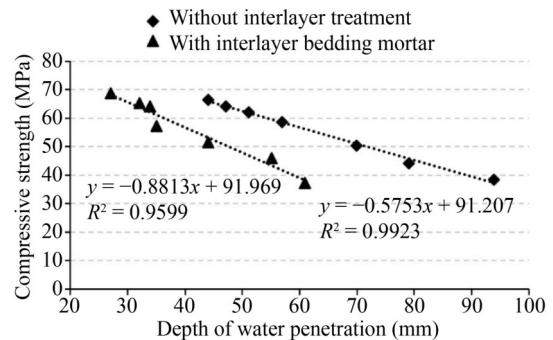


Fig. 19 Relation between depth of water penetration and compressive strength.

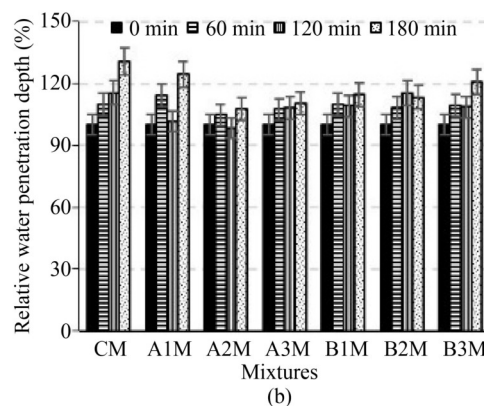


Fig. 18 28 d relative water penetration depth of specimens: (a) without interlayer treatment; (b) with interlayer mortar.

tests for compressive, splitting-tensile and flexural strengths at both day 28 and day 90. Interestingly, this effect was found to be more pronounced as the level of fly ash substitution increased. In layered castings where no mortar treatment was applied and zero-minute delay, the compressive strength decreased to 37%, split-tensile strength decreased to 32%, and bending strength decreased to 24%, while permeability increased to 65%.

3) It was found that using fly ash in part place of aggregate when making RCC reduced the optimum water content for maximum dry density, improving the concrete's mechanical properties and impermeability. In layered castings where no mortar treatment was applied and zero-minute delay, while mechanical properties improved up to 16%, permeability decreased up to 24%.

4) Increasing the time interval between placing the RCC layers resulted in the formation of more interlayer cold joints, which negatively affected the permeability, splitting tensile strength, and flexural strength more than the compressive strength, modulus of elasticity, and Poisson's ratio.

5) Regardless of the specimens' age, the interlayer cold joint reduced the moduli of elasticity of all mixes. The modulus of elasticity dropped by 1%–4% when the interlayer delay was 60 min. For the interlayer delay, it ranged from 2% to 14% and from 10% to 24% at 120 and 180 min, respectively.

6) The compressive strength of RCC showed a strong linear correlation with both flexural strength and splitting tensile strength, regardless of whether or not an interlayer treatment is used. The relationships were very close for treated and untreated mixtures as well as close to those of the conventional concrete.

7) The specimens with and without interlayer treatment show a robust linear correlation between the compressive strength and the depth of water penetration.

8) Future research might delve into a comprehensive examination of the durability and mechanical performance of roller-compacted concretes. This could include a thorough analysis of the effects of incorporating various types of pozzolans, such as fly ash, silica fume, and slag, as well as different kinds of fibers like polypropylene, steel, and glass fibers. Additionally, studies could explore the long-term performance, environmental impact, and cost-effectiveness of these materials in various construction applications.

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Competing interests The authors declare that they have no competing interests.

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