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COMPARISON OF RHEOLOGICAL AND MECHANICAL PERFORMANCES OF REPAIR MORTARS USED IN REPAIRING CONCRETE DEFECTS

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ABSTRACT

Concrete is a durable and long-lasting building material that has a wide range of uses in the construction industry. However, over time, various defects may occur in concrete structures due to various factors. These defects can threaten the safety and aesthetics of the structure and also require maintenance and repair. Among the defects seen in concrete, problems such as cracks, breaks, surface deterioration and water leaks come to the fore. Various repair techniques and materials are used in concrete repair, depending on the type and size of the defects and the intended use of the structure. One of these materials is "repair mortar". Repair mortar is a frequently preferred solution for repairing and strengthening concrete surfaces. These mortars are compatible with the natural structure of concrete and are formulated to ensure long-term durability of the repair.

In this study, the effects of repair mortars from different manufacturers on the rheological and mechanical properties in the repair of concrete road defects were investigated. The research includes a systematic comparative evaluation of materials commonly used in the market and aims to provide scientific data for material selection. Within the scope of the methodology, basic properties of repair mortars such as fluidity, setting time and strength were measured in a laboratory environment and compared with manufacturer declarations. The results revealed that the repair mortars examined complied with the technical specifications and supported that these materials are effective and reliable solutions in concrete road repair.

Keywords: Concrete repair, Repair mortar, Rheological properties, Mechanical performance.

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1 INTRODUCTION

Globally, more than 10 billion cubic meters of concrete are poured worldwide each year. In parallel, the demand for repair work to maintain the quality of concrete structures throughout their service life is increasing [1]. The growth in the repair and retrofit industry over the past 40 years has created the need for many improvements in materials, design execution, contracting processes, quality control procedures, training and more. If concrete is designed and placed properly, it will provide long-term service under normal conditions [2]. However, the structure built using concrete technology is expected to provide service for approximately 50 years under harsh conditions. Although concrete has a wide range of use in the construction industry due to its durability, it can show defects over time due to various external and internal factors [3], [4]. The reasons for these defects are very diverse and are generally related to environmental factors, application errors, material quality, structural design deficiencies and usage conditions [5]. Since concrete is a material that can be directly affected by external environmental conditions, water, temperature changes, freeze-thaw cycles and chemical interactions can negatively affect the durability of concrete. Especially moisture and water cause corrosion and cracks in the internal structure of concrete. If appropriate renovation and reinforcement solutions are not implemented, these will bring additional economic burdens and security problems [6]. Therefore, the development and widespread use of technologies to ensure that built structures continue their service life in a safe and durable manner is one of the important challenges facing civil engineers [7], [8].

In repairs to increase the structural capacity and improve driving comfort on concrete bridges and roads, the application of adding new concrete to the existing concrete surface may be preferred. To improve the structural conditions of concrete, deteriorated concrete must be removed and replaced with new materials that can repair the structural capacity of the concrete and guarantee the safety and maintenance of the component [9]. However, due to the material incompatibility between the new coating concrete and the old concrete, the connected concrete coatings may be damaged at an early age and the service life of the repair may be shortened [10], [11]. Cement-based materials are among the most widely used materials in the repair of concrete structures. Epoxy injection is also used as a repair material in concrete structures. However, although this method has the capacity to restore the pre-cracking strength of the concrete, it causes problems such as poor thermal compatibility with the sub-concrete and moisture sensitivity on the bonding surfaces during bonding. For this reason, cement-based

materials are among the most preferred repair materials because they are economical and easy to apply.

In studies on the effectiveness of cement-based repair mortars used in concrete repair, the effects of different mixing ratios, binding materials and application methods on the repair processes were investigated. Repair mortars must meet the mechanical properties of the workability criteria when fresh and the structural performance criteria when hardened [12], [13]. Fresh concrete can be bonded to hardened concrete in many situations including structural repair and reinforcement, tunnel linings, roads and pavement work, construction joints and pre-cast concrete [14]. Old and new concrete compositions have different aggregate/cement content and water/cement ratios and are exposed to different temperatures and humidity during the curing period. In addition, the development of bond strength between two concrete layers is affected by the preparation and mechanical properties of the substrate surface. In order to better understand the bonding mechanism between old and new concrete surfaces, it is necessary to measure the bond strength in the interface layer and to determine the parameters that affect these properties [15], [16]. Therefore, many studies have focused on examining the bonding mechanism between repair concrete and the existing concrete substrate. Developing and maintaining an excellent bond between concrete layers will impact repair performance results [17], [18]. Bond strength ensures that the applied coating adheres to a substrate and both concrete materials form a composite body [19], [20]. As a result, if sufficient adhesion is achieved, the structure will behave as a whole against loading and fracture stresses [21], [22].

Various studies have been conducted in the literature on the repair of concrete defects and the use of repair mortars. In these studies, many different approaches to the detection of concrete defects and the materials used to repair these defects were examined. Feng et al. [23] investigated the effect of adding carbon fiber and expansion agent to repair mortars on adhesion strength. In the study, it was found that these additives increased the adhesion strength by 33.56% and 25.18%, respectively, especially in mortars with a water/binder ratio of 0.30. In addition, it has been stated that the compressive strength ratio of the repair mortar and the base concrete being within a certain range (not more than 1.45) has a positive effect on the adhesion performance.

Santos et al. [24] concluded that the bond strength depends on the binder material in the case of concrete applications poured at different times and two hardened concrete layers bonded with repair mortar. Thanoon et al. [25] conducted a study on the effects of different repair techniques with cement mortar and epoxy injection on the structural behavior of reinforced

concrete slab. They observed that the type of repair technique affects the load capacity of the slab, causing a redistribution of stresses in both the concrete and the steel reinforcement. They concluded that all repair techniques can restore or increase the structural capacity of cracked concrete slabs.

Santos et al. [26], present an experimental study to evaluate the effect of different shrinkage and stiffness on bond strength at the interface between new and old concrete. The study shows that both parameters have a significant effect on the concrete-concrete interfacial bond strength and failure mode. This situation also affects the behavior of composite elements as it creates additional stresses at the two concrete interfaces.

Behfarnia et al. [27] generally recommend starting curing immediately after pouring the added concrete and extending it for at least 3-7 days to improve bond strength. In addition, a proper curing process will prevent maximum stresses, separation of the substrate concrete and the added concrete interface, and microcrack formation. Since no clear provisions are made for the curing procedure of composite elements cast at different times, the effect of shrinkage in two separate concretes is often neglected. They emphasized that parameters such as relative humidity and temperature and effects such as exposure to wind, rain and solar radiation should also be taken into account.

Júlio et al. [28] carried out an experimental study to evaluate the bond strength between two concrete layers of different ages. In this study, mixtures with different strengths of added concrete were taken into account. Tests have shown that increasing the compressive strength of the added concrete compared to the compressive strength of the substrate concrete improves the bond strength and the type of failure is uniform without bond failure. In addition, the study results show that the added concrete, which generally has higher compressive strength than the substrate concrete, can have an effect on the concrete-concrete bond strength.

Espeche & Leon [29] stated that there are three different stress states at the interface between old and new concrete and that the stresses are caused by the shrinkage of the repair material. In most repair applications of concrete structures, stress conditions often occur due to shrinkage of cement-based repair materials. However, it was concluded that the patch repair was subjected to pure shear and shear-tensile stresses at the bottom and tensile-shear stresses on the side surfaces.

Past research has shown how repair mortars used to repair concrete defects perform under different conditions and situations. However, it is also clear that new materials and

techniques that need to be developed to extend the life of concrete should be emphasized. In this study, the mechanical and rheological properties of repair mortars from two different companies used in concrete road construction were compared.

2 MATERIAL AND METHOD

2.1 Used materials

CEM I 42.5N Portland cement was used as a binder in the production of 150*150*150 mm concrete cube samples and 100*50 mm cylindrical samples required for experimental studies. The specific gravity of the cement used in the production of concrete samples is 3.1 g/cm^3 and the specific surface area is 3320 cm^2/g. The chemical and physical properties of Portland cement are given in Tables 1.

Table 1. Portland chemical composition

Chemical Component,%	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
Cement	63.6	19.6	4.72	3.27	1.91	0.34	1.06	4.72

The production of concrete cube and cylinder samples was carried out using two different fine and medium aggregate sizes (0/6 mm and 6/12 mm). The physical properties of the aggregates are given in Table 2.

Table 2. Physical properties of aggregates

Grain size (mm)	Moisture content %	Water absorption %	Specific weight (g/cm^3)
0/6	1.72	1.564	2.630
6/12	0.56	0.563	2.694

Within the scope of the studies, structural repair mortar was supplied from two different companies (A and B) for the production of necessary coupon samples. The amount of repair mortar mixture applied to the floors to ensure rapid setting should be prepared by taking into account the working time. If applications need to be made on old concrete surfaces, the surface must be moist and cleaned of dust and dirt before application. The technical specifications of repair mortars of companies A and B are given in Table 3. Since there is no specific standard in the production of concrete samples and repair mortars, Afyon Kocatepe University city network water was preferred.

Table 3. Technical specifications of structural repair mortars of companies A and B

Technical Properties	Repair Mortar A	Repair Mortar B
Product form	Powder	Powder
Color	Grey	Grey
Mortar density	2.3±0.1 g/cm³	2.1±0.1 g/cm³
Mix ratio	25:4.25-4.75 (powder:water)	25:5 (powder:water)
Workability time	45 minutes	45 minutes
Initial service time	24 hours	24 hours
Full curing time	28 days	28 days
Performance		
Compressive strength	≥60 Mpa (28 days)	≥45 Mpa (28 days)
Flexural strength	≥16 Mpa (28 days)	≥7,5 Mpa (28 days)

2.2 Mortar productions

Preparation of samples required for experimental studies was carried out in three stages. In the first stage, 150*150*150 mm concrete cube samples to be used in the shear tests of repair mortars were produced, and in the second stage, 100*50 mm cylindrical samples to be used in the adhesion tests were produced. The components and quantities used in the production of concrete cube and cylinder samples are given in Table 4.

Table 4. Technical properties of concrete produced with repair mortars

Components	Amounts, kg/m^3
Cement	300
Water	210
Fine aggregate	870
Medium aggregate	880
Water/Cement ratio	0.70

After sieve analysis was performed on 0/6 mm and 6/12 mm sized aggregates to be used in the mixture of concrete cube and cylinder samples in accordance with TS 3539 EN 933-1 [30] standard, both aggregate sizes were prepared to be included in the mixture at a rate of 50%.

While preparing concrete mixtures, the water/cement ratio was kept constant and cement was used as the binder (Figure 1).



Figure 1. Preparation of necessary materials for concrete cube and cylindrical samples.

When producing concrete, firstly the cement and aggregates are mixed dry in the concrete mixer. After this process, mixing water was added to the dry mixture and the mixing process was continued until a homogeneous concrete was obtained. 6 pieces of 150x150x150 mm cube samples and 12 pieces of 100*50 mm cylindrical samples were produced from the prepared concrete mixture. The concrete was placed in the molds without any gaps using a laboratory type vibration machine. Molded concrete cube and cylinder samples were kept in the laboratory environment for 24 hours until they reached sufficient hardness (Figure 2).

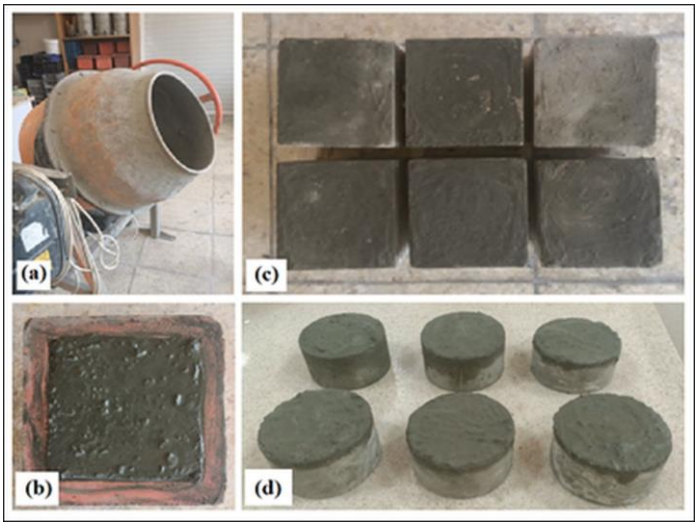


Figure 2. Preparation of the concrete samples (a) mixture (b) molding (c,d) removal from the molds.

After the hardened concrete cube and cylindrical samples were removed from their molds, they were cured in a lime-saturated water pool in the curing room at 20±2°C and 95±5% relative humidity for 28 days (Figure 3).



Figure 3. Curing of hardened concrete cube and cylinder samples.

In the final stage, the required amount of powder material and water was determined by taking into account the mixing ratios specified in the instructions for use of the repair mortars. In the laboratory type mechanical mixer, two-thirds of the mixing water was first added to the powder component and then the entire remaining part was added to the mixture and the mixing process was continued. The mixing process was terminated after a homogeneous mixture was obtained (Figure 4).



Figure 4. Preparation of type A and B repair mortar mixtures.

Cylindrical molds made of PVC pipes with a diameter of 70 mm and a height of 25 mm were placed in the center on the upper surface of the concrete cube sample prepared as the main carrier sample. Prepared repair mortar mixtures were filled into PVC molds. The cylindrical sample was placed to form a cold joint with the concrete cube sample and no chemical binder was used. Thus, it is aimed to create a slip plane at the interface during loading [31]. Coupon samples on the top layer of concrete were kept in the molds for the first 24 hours. After 24 hours, the samples were removed from the mold and cured by keeping them in the laboratory under normal working conditions, without exposure to rain, wind and sun. Temperature and

relative humidity conditions were assumed to be constant throughout the curing period (Figure 5).



Figure 5. Samples produced for shear tests with type A and B repair mortars.

For bond strength, a coupon sample made of repair mortar was placed between two cylinder samples to form a triple composite sample of concrete-repair mortar-concrete. The samples were aligned by centering during bonding and no gaps were left at the contact surfaces. Three samples were prepared for each repair mortar (Figure 6).



Figure 6. Samples produced for adhesion testing with type A and B repair mortars.

2.3 Experiments

In the experimental studies, the spreading test, solidification time and temperature tests, and 4 and 6 hour and 7 and 28 day strength tests were performed while the repair mortar was added to the hardened concrete sample and into the coupon layer while it was fresh. While evaluating the experimental study results, the arithmetic average of three samples was taken.

2.3.1 Flow value

The spreading test of the mixtures prepared from A and B type repair mortars was carried out by placing them in a mini cone on the spreading table according to TS EN-12350-6 [32]. After the mini cone on the table was pulled upwards, the table was shaken 15 times with its arm to spread the mortar on the table. For both repair mortars, the spreading diameters were measured in a perpendicular direction to each other and their arithmetic averages were taken (Figure 7).



Figure 7. Determination of spreading diameters of A and B type repair mortars.

2.3.2 Determination of spreading diameters of A and B type repair mortars

The hardening time was determined by lowering the Vicat needle freely into the A and B type repair mortar placed on the Vicat cone at certain intervals. The penetration values of the Vicat needle were recorded in mm at each minute. At the same time, a thermocouple was immersed into the repair mortar placed in another Vicat cone and the apparent solidification temperature during solidification was recorded (Figure 8).



Figure 8. Determination of the setting time of repair mortars.

2.3.3 Shear strength

In order to determine the shear strength of repair mortars to existing concrete, the prepared composite sample was laid on its side and subjected to shear loading. Thus, the contact surface between the repair mortar and the concrete sample was determined as the slip plane. A metal load transfer device is positioned to apply a pushing force from the edge of the cylindrical mortar sample. The concrete cube sample was fixed from the opposite direction and its resistance against loading was ensured, aiming to displace only the repair mortar sample in the sliding direction. With the help of a hydraulic pressure device, the applied load is increased at a controlled rate. During loading, the load increase continued until the adhesion between the repair mortar sample and the concrete surface was broken. The specimens generally fractured at the interface on the bottom surface of the circular segment, indicating that sufficient load accumulation occurred on the shear plane. In some samples, cracks other than shear fractures were also observed; this situation can be explained by the effect of local stresses [33]. The maximum fracture load of the sample at the time of fracture was recorded at 4 and 6 hours and 7 and 28 days (Figure 9).



Figure 9. Shear test on repair mortars.

The shear strength was calculated according to Relation 1, based on the contact surface between the cylindrical sample produced from the repair mortar and the concrete cube sample.

$$\sigma_s = N/A \quad (1)$$

In the relation, σ_s represents the shear stress; N represents the maximum breaking load of the samples; A represents the cross-sectional area of the samples.

2.3.4 Bond Strength

In direct tensile strength testing, very efficient results cannot be obtained since the area of the bonded surface exposed to loading is smaller compared to the sample volume. In such tests, only a very small part of the bonded plane is subjected to maximum stresses [34]. The direct tensile strength of concrete is considered as an indicator of tensile strength and ASTM C496 [35] standard is applied [36]. The prepared three-piece composite sample was placed in the testing machine in a vertical position for the test. Both concrete blocks of the sample were fixed to the upper and lower plates and positioned so that the load would be applied in the tensile axis. The loading was applied equally and controlled in opposite directions to the upper and lower concrete blocks of the sample with the help of a hydraulic pressure tensile device. Thus, a tensile force was transferred to the repair mortar sample in the direction of adhesion and the loading was continued until fracture occurred under the effect of this force. During the experiment, the maximum tensile force was recorded at 4 and 6 hours and 7 and 28 days (Figure 10).



Figure 10. Bond strength in repair mortars.

The bond strength was calculated according to Relation 2 according to the contact surface between the cylindrical sample produced from repair mortar and the concrete cylindrical sample.

$$\tau = V/A \tag{2}$$

In the relation, τ represents the bond stress; V represents the maximum breaking load of the samples; A represents the cross-sectional area of the samples.

3 RESULTS AND DISCUSSIONS

After collecting the data from the experimental studies on A and B type repair mortars, the necessary evaluations were made.

3.1 Spreading test

As a result of the spreading test, the spreading diameter value of type A repair mortar was determined as 300 mm and the spreading diameter value of type B repair mortar was determined as 240 mm. The spreading diameter values of type A and B repair mortars are shown in Figure 11. Type A repair mortar has more fluidity than type B repair mortar. This suggests that type A may spread more easily and penetrate narrow and hard-to-reach spaces better, but may also increase the risk of uncontrolled spread and segregation. In contrast, it shows that type B repair mortar, with its lower spreading diameter, can offer better shape stability during application and may be more advantageous in repairs on vertical surfaces. Similarly, Neville [37] stated in his study that the workability of fresh mortars should be adjusted according to the application method.

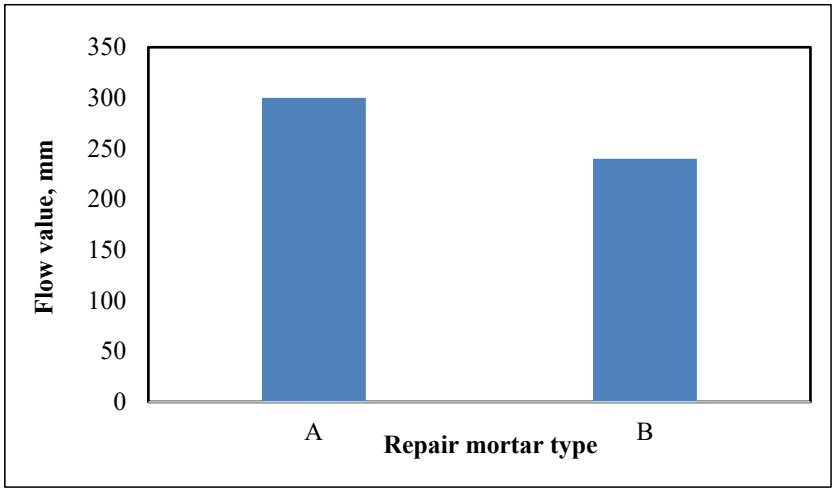


Figure 11. Spreading diameter values of type A and B repair mortars.

3.2 Setting time and apparent solidification temperature determination test

The solidification process and sinking depths of type A and B repair mortars using Vicat needles and truncated cone shaped molds are presented in Figure 12. For both repair mortars, the initial penetration depth of the Vicat needle was measured as 40 mm and the test was continued until the needle failed to fully penetrate into the mixtures.

During the first 10 minutes, it was observed that the penetration depths of type A and B repair mortars measured with the Vicat needle were quite close to each other. This shows that both mortars exhibit similar rheological behavior in the early stage [38].

However, starting from the 10th minute, a rapid decrease in the penetration depth of the type B repair mortar was observed and it was determined that this mortar started to set more quickly. As a result of the measurements, the complete solidification time of type B repair mortar was determined to be approximately 40 minutes and type A repair mortar was determined to be approximately 50 minutes. This finding revealed that type B repair mortar exhibited a faster hardening behavior and therefore offered a shorter "open working time". Mehta and Monteiro [39] emphasized that the short setting time can provide a significant advantage in repair works requiring rapid intervention in field applications.

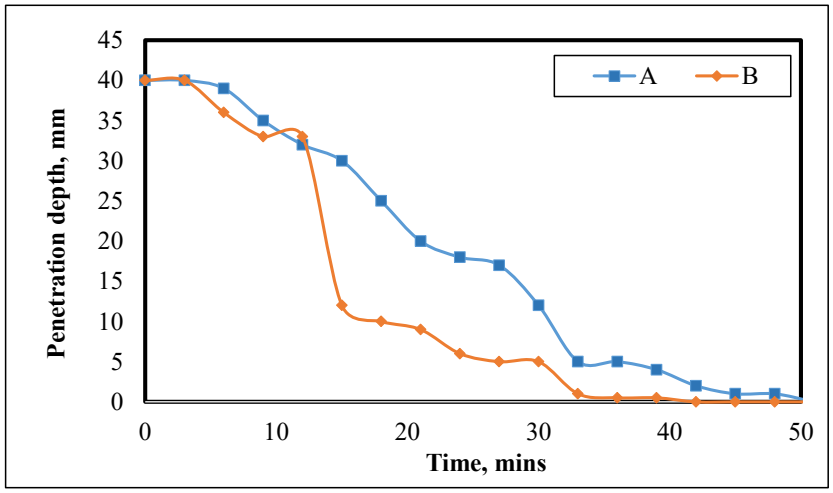


Figure 12. Vicat penetration depths of repair mortars.

The reaction temperatures of the repair mortars placed in the other Vicat cone were measured with thermocouples until they solidified and the solidification times were recorded. Type A repair mortar revealed a temperature of 29 ºC after approximately 50 minutes of solidification time, and type B repair mortar revealed a temperature of 25 ºC after approximately 40 minutes of solidification time. When the data was examined, it was seen that type A mortar solidified in a longer time, but produced more heat in this process. Juenger et al. [40] explained this situation by saying that the mortar may contain higher amounts of slower reacting binders. The maximum temperature values recorded for both repair mortars started to decrease towards room temperature when solidification was completed (Figure 13).

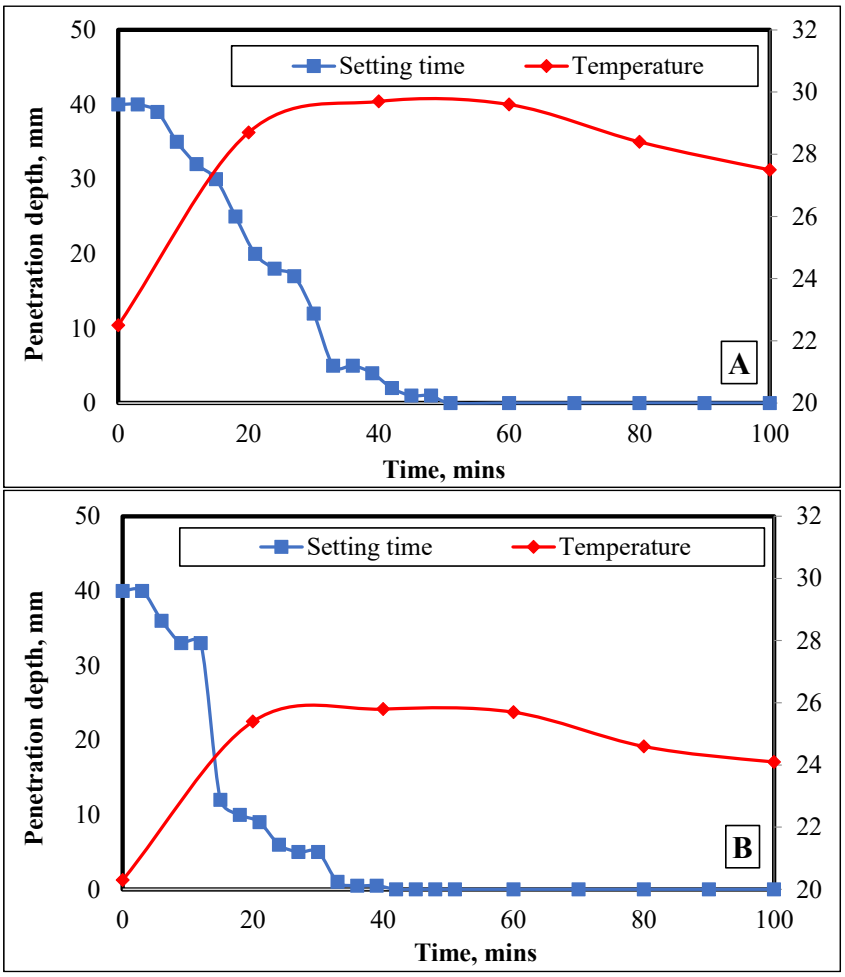


Figure 13. Setting time and apparent solidification temperatures of type A and B repair mortars.

3.3 Shear strength

The 4 and 6 hour shear stress values in contact with the surfaces of the repair mortar samples were determined to be approximately 32 and 42 kPa for type A repair mortar and approximately 18 and 15 kPa for type B repair mortar. While type A repair mortar gained early strength and its strength increased over time, the strength of type B repair mortar decreased over time. Type A mortar shows significantly higher shear strength than type B at an early age (Figure 14). This means that type A is more suitable for situations where early intervention or rapid repair is required [41].

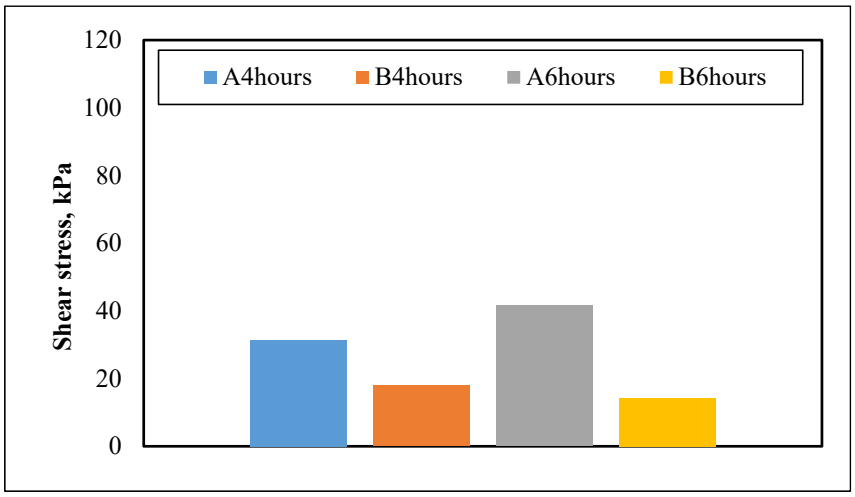


Figure 14. 4 and 6 hours shear stresses of A and B type repair mortars.

Type A repair mortar shows a continuous increase in shear strength, with approximately 57 kPa at 7 days and 72 kPa at 28 days. Type B repair mortar exhibits a decreasing performance over time with a shear strength of approximately 32 kPa at 7 days and 25 kPa at 28 days. Type A mortar shows much higher strength compared to type B, not only at an early age but also in the long term. The 28-day strength of type B mortar was lower than the 7-day strength (Figure 15). This probably suggests embrittlement, weak bond formation or lack of resistance to environmental effects within the material [42], [43].

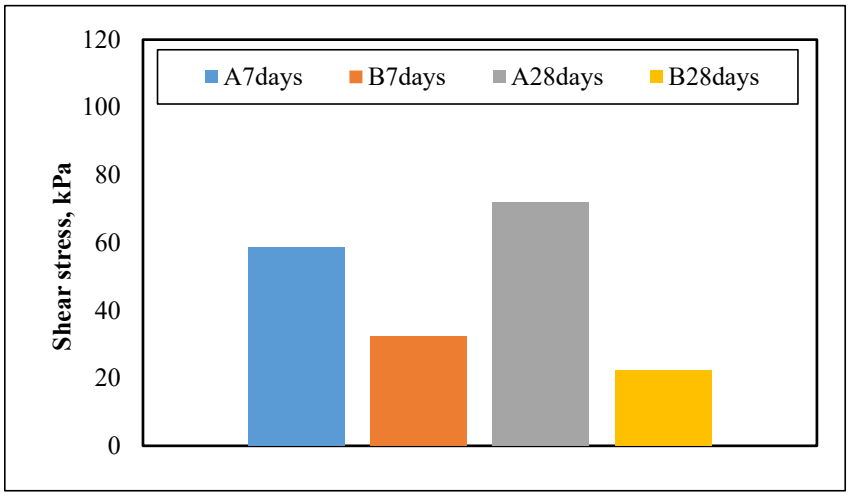


Figure 15. 7 and 28 days shear stresses of A and B type repair mortars.

3.4 Bond strength

While the 4-hour maximum stress value of type A repair mortar reached approximately 65 kPa, the maximum stress value of type B repair mortar remained around 8-9 kPa. At the end

of 4 hours, the bond strength of type A repair mortar was much higher than type B, indicating that type A repair mortar gained mechanical integrity faster.

The maximum tensile value of the A type repair mortar at 6 hours was approximately 70 kPa, but the breaking point occurred at a slightly lower elongation than at 4 hours. The maximum stress value of type B repair mortar decreased further after 4 hours and reached approximately 5-6 kPa. However, in general, the bond strength remained well below the type A repair mortar. This suggests that type A shows a more effective hydration process and mechanical bonding development [44]. Low bond strength and deformation tendencies may suggest that late hydration and more porous structures were formed in type B mortar (Figure 16). These findings are consistent with the findings of Saha & Ghosh [45] that adherence development is directly related to microstructure formation. In their studies, Saha and Ghosh stated that the development of early-age bond strength depends on both the setting speed and the microstructure formation rate in repair mortars.

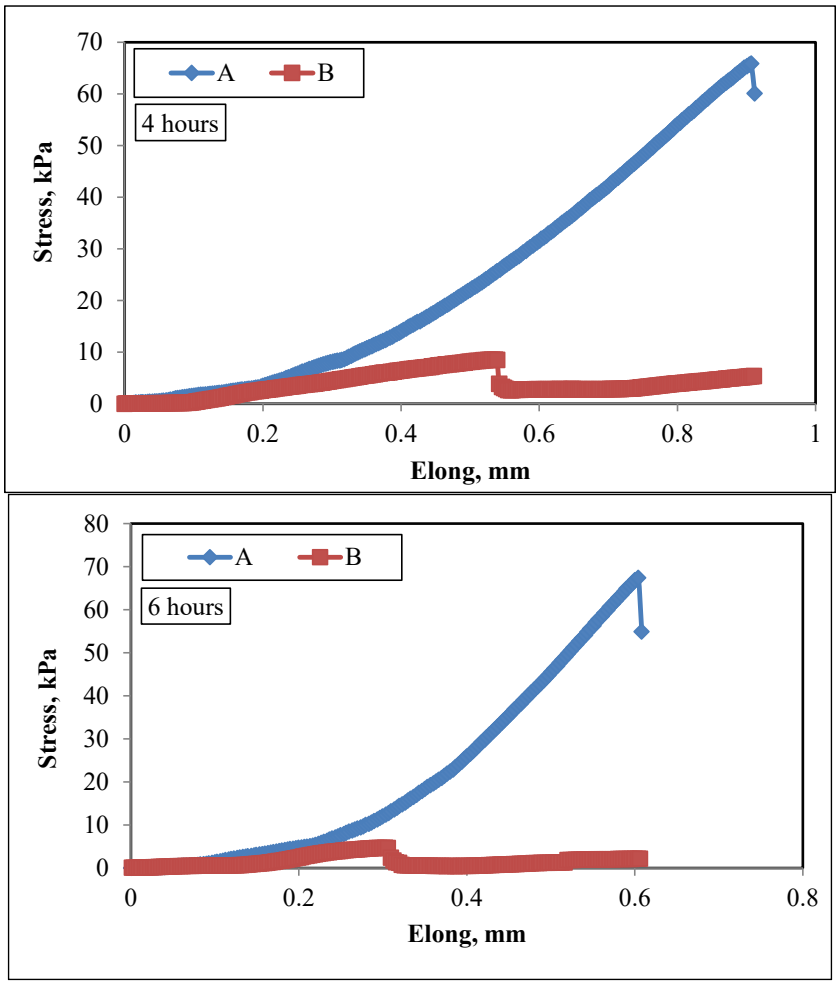


Figure 16. 4 and 6 hour bond strengths of type A and B repair mortars.

Type A repair mortar reached higher adhesion strength (~60 kPa) at 7 days. This indicated that it had a mortar characteristic that sets late and therefore forms a strong bond over time. At the same time, allowing more deformation (~0.7 mm) showed that type A repair mortar exhibited a ductile behavior and was advantageous in terms of crack control. Type B repair mortar reached the maximum stress value (~40 kPa) faster but ruptured earlier (~0.55 mm). When the behavior of the mortar was examined, it was seen that it had a brittle character and a low deformation tolerance structure [46], [47].

On the 28th day, type A repair mortar reached a much higher bond strength value (~72 kPa), then a sudden decrease occurred and then rupture occurred. Although type B repair mortar showed good performance at an early age, its adhesion development (~15 kPa) remained weak in the long term. Basheer et al. [48] stated that the long-term performance of repair mortars depends on the setting and hydration process of the material and environmental conditions (Figure 17).

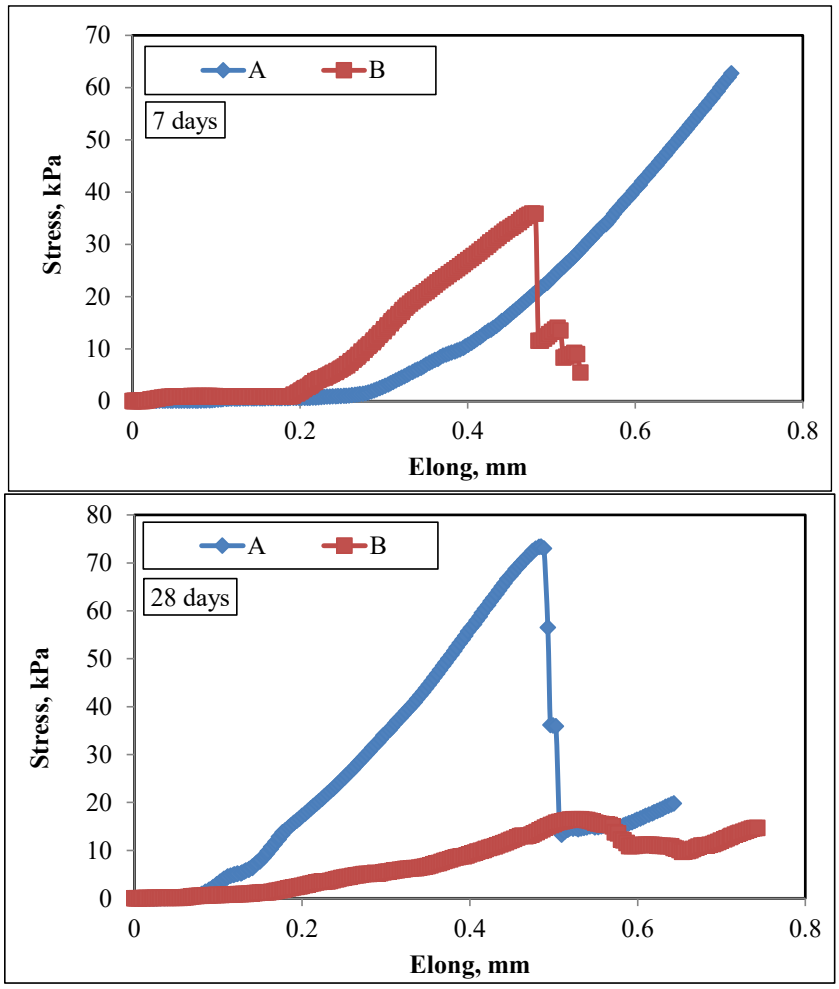


Figure 17. 7 and 28 day bond strengths of type A and B repair mortars.

4 CONCLUSION AND SUGGESTIONS

In this study, the rheological properties, setting times, adhesion and shear strengths of two different repair mortars, type A and B, used in the repair of concrete surface defects were compared. The changes for both repair types were examined and the results obtained were evaluated.

- According to the spreading test results, type A repair mortar exhibited higher fluidity. This will provide a significant advantage in filling narrow cracks and hard-to-reach areas. This feature can be preferred in practical applications, as it will provide effective penetration and gap filling, especially on concrete road surfaces where micro cracks are common. However, this high fluidity requires careful application as it can increase the risk of segregation and uncontrolled spreading on non-horizontal surfaces. Type B mortar offers a more stable application with a lower spreading diameter, and will yield positive results especially in vertical surface repairs.
- In terms of setting time, type B mortar tended to harden faster. This will save time in case of urgent repairs or in field conditions where the next process step needs to be implemented quickly. However, the slower setting of type A mortar produces more heat during the setting process, indicating an intense hydration process in the internal structure, and it is thought that this contributes positively to the mechanical performance.
- In terms of bond strength, type A repair mortar showed higher strength than type B repair mortar at all ages. Over the period from 4 hours to 28 days, type A mortar exhibited both a stronger and more ductile behavior, which was evaluated positively in terms of crack control and long-term durability. Although type B mortar initially performed relatively acceptable, over time its bond strength decreased significantly and it tended to become brittle. This shows that, especially in the repair of concrete roads exposed to heavy traffic loads, the mortar may lose its bearing capacity over time, leading to new deteriorations.
- Shear strength results also similarly revealed the superiority of type A mortar. Rapid strength gain at an early age will allow type A to perform safe repairs in areas exposed to sudden loads such as road surfaces. In addition, while type A mortar continues to increase its strength over the 28-day period, the tendency for the strength to decrease in type B mortar indicates that it will offer a limited solution in terms of long-term performance.

As a result, it was determined that type A repair mortar is a more suitable option in terms of both allowing early intervention and providing long-term strength in the repair of concrete defects and especially in field applications requiring high strength and continuity such as concrete roads. Type B mortar can be preferred for small-scale repairs requiring shape stability where working time is limited, thanks to its rapid setting advantage. However, when evaluated in general, type A repair mortar stands out as a more reliable solution in concrete repair applications with its higher mechanical performance and durability. The data obtained revealed significant differences in both early age and long-term performance and showed how critical material selection is, especially in field applications.

Statement of Research and Publication Ethics

This article does not involve any studies with human participants or animals conducted by any of the authors.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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