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Use of Waste Tire Rubber Alkali-Activated-Based Mortars in Repair of Concrete Structures

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Abstract**—**Reinforced concrete structures experience local defects such as cracks over their lifetime under various environmental loadings. Consequently, they are repaired by mortars to avoid detrimental effects such as corrosion of reinforcement, which in long-term may lead to strength loss of a member or collapse of structures. However, repaired structures may need multiple repairs due to changes in load distribution, and thus, lack of compatibility between mortar and substrate concrete. On the other hand, waste tire rubber alkali-activated (WTRAA)-based materials have very high potential to be used as repair mortars because of their ductility and flexibility, which may delay failure of repair mortar, and thus, provide sufficient compatibility. Hence, this work presents a study on suitability of WTRAA-based materials as mortars for repair of concrete structures through an experimental program. To this end, WTRAA mortars with 15% aggregate replacement, alkali-activated (AA) mortars, and ordinary mortars are made to repair a number of concrete beams. The WTRAA mortars are composed of slag as base material, sodium hydroxide as alkaline activator, and different gradation of waste tire rubber (fine and coarse gradations). Flexural tests are conducted on the concrete beams repaired by the ordinary, AA, and WTRAA mortars. It is found that, despite having lower compressive strength and modulus of elasticity, the WTRAA and AA mortars increase flexural strength of the repaired beams, give compatible failures, and provide sufficient mortar-concrete interface bondings. The ordinary mortars, however, show incompatible failure modes. This study demonstrates promising application of WTRAA mortars in practical repairs of concrete structures.

Keywords—Alkali-activated mortars, concrete repair, mortar compatibility flexural strength, waste tire rubber.

I. INTRODUCTION

A. Background

REPAIR and retrofit of reinforced concrete structures have become a priority in recent years due to climate change and aging effects. Generally, repair techniques are used to remedy local and minor defects such as cracks, which may propagate over time, or perhaps may expose reinforcement to corrosive environments [1]-[3]. However, retrofit strategies are implemented to restore strength and serviceability of concrete structures [3], [4]. In addition to time efficiency and cost effectiveness aspects, repair of existing concrete structures increases their lifespan and helps achieve a more sustainable environment, compared to demolition and construction of new structures.

Concrete material deteriorates for many reasons: chemical corrosions [5], mechanical (anomaly stress and fatigue) [6], [7], and chemical-mechanical cause (creep and shrinkage) [8], [9]. The compatibility between repair material and substrate concrete is of paramount importance, and it exists when the repaired region (including substrate concrete and repair material) sustains all the stresses from external loadings without failure, same as undamaged concrete beam. Therefore, if the repair material decreases flexural strength of the repaired beam, in comparison with the undamaged concrete beam, the repair material fails prior to the failure of the substrate concrete, and so, the repair becomes incompatible. The compatibility is characterized as a physical, chemical, and electrochemical balance that allows repair process to work properly [10], [11]. National Institute of Standards and Technologies (NIST) recommends a flexural strength test to determine the compatibility of repair mortar and concrete [12]. According to this test, a surface for repair should be considered when molding concrete beams. The compatibility can then be determined through comparing the failure of a control beam (undamaged beam) with repaired beams.

Fig. 1 shows exemplar compatible and incompatible failure modes of the concrete beams repaired by mortars [13]. As seen, there are two compatible failure modes: (a) both substrate concrete and repair mortar fail at the repaired region, and (b) failure occurs outside the repaired region, and both substrate concrete and repair mortar remain intact. Also, there are three incompatible failure modes: (c) failure occurs at the edge of the repaired region, where substrate concrete fails at the edge of the repaired region through inclined cracking, and the repair mortar remains intact, (d) failure occurs at the center of the repaired region; however, only the substrate concrete fails through inclined cracking, and the repair mortar remains intact, and (e) similar to (d), but vertical cracking of the substrate concrete.

It has been reported that only flexural strength test is insufficient to determine compatibility between repair mortar and substrate concrete, and compatibility depends on the elastic moduli of the mortar and concrete, too. Additionally, flexural and tensile strength of the repair mortar can have a significant impact on compatibility, and high-shrinkage mortars are also found to cause incompatibility [15]. If the repair mortar is weaker than the substrate concrete, the mortar-to-concrete compressive strength ratio, mortar-to-concrete elastic modulus ratio, and undamaged repaired-to-repaired undamaged beam flexural strength ratio (hereafter, for abbreviation, they are called compressive strength ratio, elastic modulus ratio, and flexural strength ratio, respectively) are expected to be less than 1. As a result, compatible failure occurs around the center of the beam (Fig. 1 (a)), while incompatible failure occurs near the

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corner. If the flexural strength ratio is greater than 1, the repair material is compatible, and the location of the failure becomes unimportant due the fact that the repaired beam can carry higher load compared to the undamaged beam [14]. Further, in certain studies based on finite element modelling of repaired beams by ordinary mortars, it was reported that the repair is compatible if the elastic modulus ratio falls within the range of 0.7-1.3 [7], [13]. Particularly at elastic modulus ratio of around 0.7, lower tensile stress concentrations exist in repair mortar and substrate concrete, and hence, good quality bonding between mortar and concrete leads to a compatible repair. For elastic modulus ratio of around 1.3, higher tensile stress concentrations occur in the concrete at mortar-concrete interface, and consequently, the concrete's failure initiates from the middle of the beam due to the higher compressive strength of the mortar [7], [13].

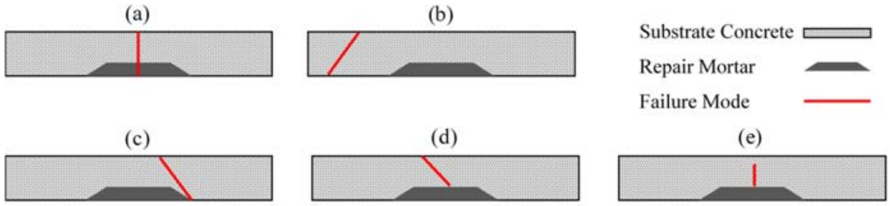

Fig. 1 Various failure modes of repaired beams: (a) compatible failure, (b) compatible failure, (c) incompatible failure, (d) incompatible failure, and (e) incompatible failure [14]

B. Previous Studies on Repair Mortars

Many mortars have been developed for repair of concrete structures, so far. The most commonly used repair mortars are cement-based ordinary mortars, supplemented with various components such as additives. Ordinary mortars have several drawbacks, including high cement content and short service life, both of which contribute to high carbon emissions [16]-[18]. Concrete structures have also been repaired with polymer-modified cement (PMC) mortars, which have better mechanical and durability properties than ordinary mortars [19], ultra-high-performance (UHP) mortars, which have high cost and high autogenous shrinkage [20], engineered cementitious composite (ECC) mortars, which have self-healing properties [21]. However, all these mortars contain high amount of cement (cementitious materials), which is not in line with low-carbon technology and sustainable development. Hence, use of AA mortars has been highly recommended and emphasized due to their lower carbon emissions and higher durability. Strong interface bonding is produced when slag and sodium hydroxide (NaOH) are combined, according to research [22], [23]. It was reported that ground granulated blast-furnace slag-based mortars form a strong bond with substrate concrete because of their high calcium content. Excessive amounts of calcium produce more calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H), which create a stronger mortar-concrete interface, while fly ash causes a weaker interface bonding [23]. Ordinary mortars, AA mortars, and PC mortars have also been used in some studies to investigate repair of reinforced concrete beams [16], [24]-[26]. The influence of different types of mortar was explored, resulting in better performance of AA mortars compared to PMC mortars [16]. Due to high potential of AA mortars, they could reach a compressive strength of 30 MPa in just 24 hours [24]. In a different study, PMC mortars were used to repair 1 mm wide cracks in reinforced concrete beams, where the flexural strength of the repaired beams increased [27].

Design guidelines and standards (e.g., EN1504-3 and ACI 546-3R) give recommendations on how to select an appropriate repair material and measure its quality. Repair durability and repair mortar compatibility with substrate concrete are the main shortcomings of these recommended provisions [28], [29]. The ACI 546-3R recommends a repair strategy based on the magnitude of concrete damage rather than a thorough characterization of the repair material. EN 1504-3 specifies the type and characteristics of the repair mortar based on the function of the damaged member (structural and non-structural). It also suggests limitations on compressive strength, adhesion resistance, modulus of elasticity, shrinkage, existing chlorine ions, and carbonation resistance of the repair mortar. According to EN 1504-3, the core difference between structural and non-structural mortars is their compressive strength. Structural mortars must have a minimum compressive strength of 45 MPa. However, incompatibility could be caused by large differences in the compressive strength of repair mortar and concrete [30]. Mortars with high compressive strength are not only incompatible with substrate concrete, but they also decrease repair life [13].

C. Research Contribution

As the survey above demonstrates (Section I *B*), AA mortars can create strong interface bonding between repair mortar and substrate concrete. On the other hand, no research exists on the potential use of waste tire rubber (WTR) in AA mortars as repair materials although WTRs have the potential to increase ductility and flexibility [31], [32]. Indeed, WTRs can increase the durability of rendering mortars [33]. Recently, Eren et al., found that WTRAA concrete has lower elastic modulus and compressive strength and higher flexural and tensile strengths compared to ordinary concrete [34]. Further, Ameri et al. suggested potential use of WTRAA mortars in repair of damaged concrete [35]. Hence, this work studies use of WTRAA mortars in repair of concrete beams through an experimental program. To achieve this aim, a number of concrete beams are constructed, damaged, and repaired by ordinary, AA, and WTRAA mortars. Compressive strength of substrate concrete and mortars are measured, and their elastic moduli are empirically computed. Three-point flexural tests are conducted on the repaired beams. The compatibility of the mortar and concrete is determined through failure modes of the repaired beams, and is related to the compressive strength ratio, elastic modulus ratio, and flexural strength ratio. Further, the adequacy of mortar-concrete interface bonding for WTRAA mortars is discussed. Finally, to see the influence of pre-loading on the repaired beams, some damaged beams are loaded prior to being repaired by ordinary mortars.

II. EXPERIMENTAL PROGRAM

In this section, the experimental program, including concrete beams, repair mortars, and testing procedure, is described.

A. Concrete Beams

To study the compatibility of various types of mortars, a number of concrete beams needs to be constructed, repaired, and tested. A mix is designed for the substrate concrete: 28-days compressive strength of, $f_c = 30$ MPa, water-cement ratio (W/C) of 0.4, and slump of 10 cm. Table I details the mass density of various constituents of the substrate concrete. Fig. 2 shows aggregate gradation curve of the concrete. The maximum size of the coarse aggregate is 12.5 mm, and both fine and coarse aggregates are used in a saturated surface-dry condition. Further, to improve the workability of the concrete, a poly carboxylate superplasticizer is added. The concrete beams are 100 mm × 100 mm × 500 mm, and cured for 28 days [36].

TABLE I
MASS DENSITY OF THE CONCRETE AND ITS VARIOUS CONSTITUENTS

Cement	Fine Aggregate	Coarse Aggregate	Super Plasticizer	Concrete
400	835	1031	2	2350

All values are in kg/m^3

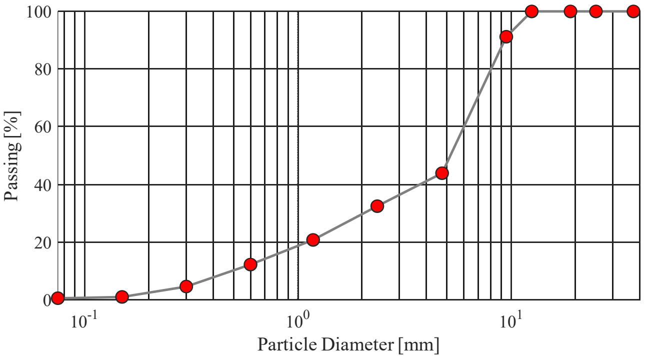

Fig. 2 The aggregate gradation curve of the substrate concrete

Damages need to be created in the concrete beams first, and then repaired by the mortars. Fig. 3 shows the location of the damages and dimension of the repaired beams and repaired regions. Two different damage locations are considered: center (Fig. 3 (a)) and corner (Fig. 3 (b)) of the beams. The center of the beam is the location of the vertical flexural cracks in concrete beams, and hence is used to assess the compatibility of the mortar and substrate concrete. The corner repair is used to assess the mortar-concrete interface bonding. So, if the mortar-concrete interface bonding is insufficient and delamination occurs, the beam would fail at the left side of the repair edge (S2, smaller cross section). This was also experimentally checked and verified by flexural testing of some corner-damaged and unrepaired beams, and all the beams were failed at S2, as expected.

The hollow repaired regions are first constructed through using wedge-shape wooden pieces, which will be substituted with the repair mortar after curing the concrete beams. The wooden piece is 170 mm long at the bottom and 155 mm long at the top with the thickness of around 15 mm for the center repair (see Fig. 3 (c)).

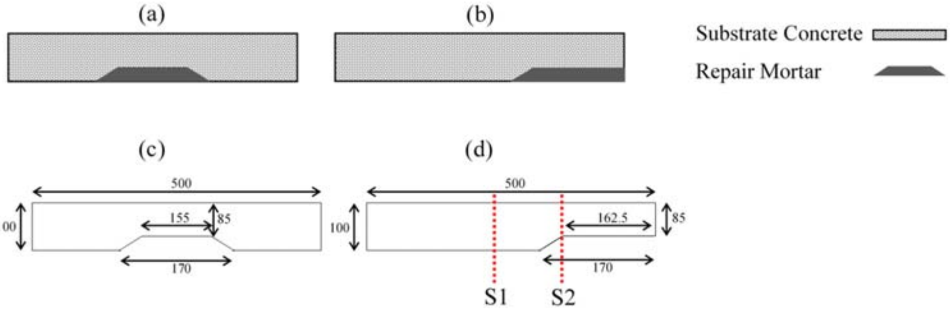

Fig. 3 The repaired concrete beam (all dimensions are in mm): (a) center-repaired, (b) corner-repaired, (c) dimension of the center-repaired beams, and (d) dimension of the corner-repaired beams

In this study, a total of 30 concrete beams are constructed and tested in flexure. Three undamaged beams without any repair are constructed and used as control beams. For the repaired beams, four different types of repair mortar are used (see Section II *B* for further details on the repair mortars), and each mortar is used to repair six beams: three center-repaired beams and three corner-repaired beams. In addition, three beams are loaded first, and then repaired by ordinary mortars to see the effects of pre-loading on the repaired beams. For the pre-loaded beams, the flexural strength of the beams is measured first, and then a static load equal to 60% of the ultimate flexural strength of the beam is applied before the repair process. For all the repaired beams, the substrate's concrete surface is treated with water and a wire brush before applying the repair mortar to ensure a strong bonding.

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The 3-point flexural strength test is conducted on the beams in accordance with ASTM C293-16 [37]. The vertical load is applied to the center of the beams, and the test continues until the concrete beam is entirely fractured. To minimize possible discrepancies in the results of the tests, the humidity of the samples checked to be in same conditions.

B. Repair Mortars

In this work, four different types of repair mortar are used: (1) ordinary mortar, (2) AA mortar, (3) WTRAA1 mortar, and (4) WTRAA2 mortar. All the mortars have W/C of 0.4. The detailed constituents of each mortar are shown in Table II. The maximum aggregate size of ordinary mortars and AA mortars is 4 mm (fine sand), while this value is 6 mm in WTRAA mortars. As shown in Fig. 4, two different gradations of WTR are used here: powder rubber whose particles are 0-3 mm, and crumb rubber whose particles are 2-6 mm. For the WTRAA1 mortar, crumb-to-powder ratio is 2:1 while for the WTRAA2 mortar, crumb-to-powder ratio is 1:2. Thus, the WTRAA1 mortar has a finer gradation compared to the WTRAA2 mortar. The sodium hydroxide (NaOH) in its liquid form with concentration of 12 mol is used and added to the ordinary, AA, WTRAA1, and WTRAA2 mortars. This solution is created using water and then cooled down.

TABLE II
MASS DENSITY OF VARIOUS CONSTITUENTS OF THE REPAIR MORTARS

Mortar Type	Cement	Slag	NaOH	Powder rubber	Crumb rubber	Fine sand	Super plasticizer
Ordinary	550	-	-	-	-	1652	3
AA	-	600	96	-	-	1450	-
WTRAA1	-	600	96	72.5	145	1232.5	-
WTRAA2	-	600	96	145	72.5	1232.5	-

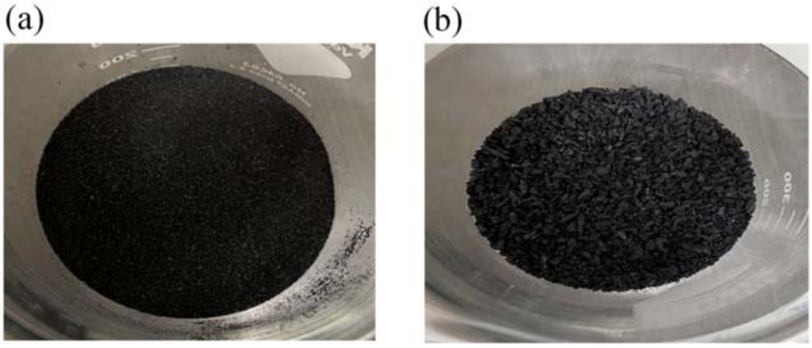

Fig. 4 Different types of WTR used: (a) powder rubber (0-3 mm), (b) crumb rubber (2-6 mm)

The beams repaired by the AA, WTRAA1, and WTRAA2 mortars are cured using an oven, set to 55 °C for 3 days and kept in laboratory condition for 28 days. Further, the beams pre-loaded and repaired by ordinary mortar are cured in water until the age of 28 days. The compressive strength and unit weight of each mortar are also measured [38], which will be used as input variables to empirically compute elastic modulus (see Section III, (1)). Three cubic samples (100 mm x 100 m x 100 mm) for the substrate concrete and each of the mortars are constructed, and tested according to BS EN 12390-1 [39] using compressive strength machine at the ages of 1 day, 3 days, and 28 days. The unit weight test is also performed according to ASTM138-17 [38].

III. RESULTS AND DISCUSSION

The average of the test results is provided and discussed in this section. It is worth mentioning that the coefficient of variation for the samples was checked and it was too small.

A. Compressive Strength and Elastic Modulus

Based on the mix design described in Section II *A*, the theoretical compressive strength of the substrate concrete is around 30 MPa at the age of 28 days. The test results show that the mean concrete compressive strength is 32 MPa at the age of 28 days. Fig. 5 shows the mean compressive strength of the mortars. The ordinary mortar has the highest compressive strength, slightly more than 20 MPa. The mean compressive strength of the AA mortar is around 1 MPa less than that of the ordinary mortar. It is worth mentioning that the ordinary mortar contains cement, and has already reached about 90% of its ultimate compressive strength by the age of 28 days (test day), but the AA mortar takes less time to build up strength due to its pozzolanic basis [23]. However, after three days in the oven, the AA, WTRAA1, and WTRAA2 mortars have gained a significant percentage of their ultimate compressive strength at the age of 28 days. The mean compressive strength of the WTRAAM1 (which contains 10% crumb rubber and 5% rubber powder) and WTRAAM2 (which contains 10% rubber powder and 5% crumb rubber) has been reduced by around 50%. Therefore, adding WTR to the AA mortars highly decreases compressive strength. Based on the previous studies, rubber particles are flexible under compression, and it can be the reason of compressive strength reduction [34], [40]. Further, there is a 1.2 MPa difference between the mean compressive strength of the WTRAA1 and WTRAA2 mortars. The use of crumb rubber gives a higher compressive strength compared to powder rubber. This is because a finer material creates a weaker mortar-concrete interface bonding [41].

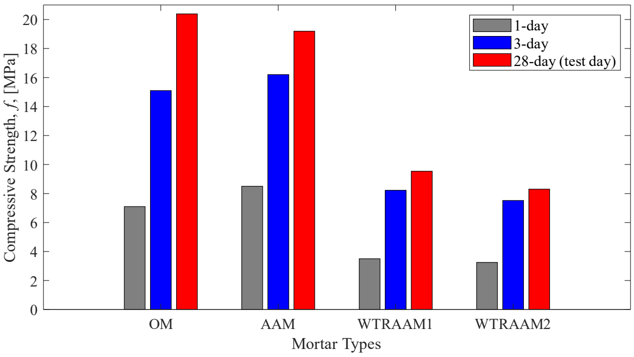

Fig. 5 Compressive strength results of the mortars

TABLE III
CALCULATED ELASTICITY MODULES FOR SPECIMENS

Material	f (MPa)	γ	k_1	k_2	E (MPa)
Concrete	32	2.35	1	1	26047
OM	20.4	2.03	1	1	16728
AAM	19.2	2.17	1	0.95	17796
WTRAAM1	9.5	1.9	1	0.95	10791
WTRAAM2	8.3	1.9	1	0.95	10316

Although there are many proposed relationships to determine elastic modulus of concrete and mortar, only a few of them has considered the effect of additives and the type of aggregates. In this study, to determine elastic modulus of concrete and mortar, following relationship is used, which accounts for the effects of additives, coarse aggregate type, compressive strength, and density [42]:

$$E = 3.35\times10^4 \times k_1 k_2 \left(\frac{\gamma}{2.4}\right)^2 \left(\frac{f}{60}\right)^{0.33} \tag{1}$$

where k_1 and k_2 are factors for coarse aggregate and additives (slug and fly ash), respectively; γ is unit weight; f is mean compressive strength (MPa), and E is elastic modulus (MPa). This relationship was derived from over 3,000 tested samples and has an accuracy rate of 95%. Table III summarizes the results of the computed elastic moduli. The flexibility of WTR appears to reduce the elastic modulus of the mortars (see Table III).

B. Repaired Beams

Fig. 6 shows exemplar failure modes of the center- and corner-repaired beams in flexure, and Table IV presents the results of the mean flexural strength of the center-repaired beams. The center-repaired beams are used to assess compatibility. As seen in Table IV, the mean flexural strength of the three undamaged beams is 4.68 MPa, and the beams failed in the center, as expected. Figs. 6 (a) and (e) show failure modes of the beams repaired by ordinary mortar as well as the beams pre-loaded and repaired by ordinary mortar. The failure occurs at the edge of the repair region, which shows the incompatibility between mortar and concrete. These beams have a flexural strength ratio of 1, but elastic modulus and compressive strength ratios of less than 1. Further, the beams preloaded and repaired by ordinary mortar gives the same failure mode, flexural ratio, compressive strength ratio, and elastic modulus ratio. This means the pre-loading does not affect the repair and behavior of the beams repaired by the ordinary mortar.

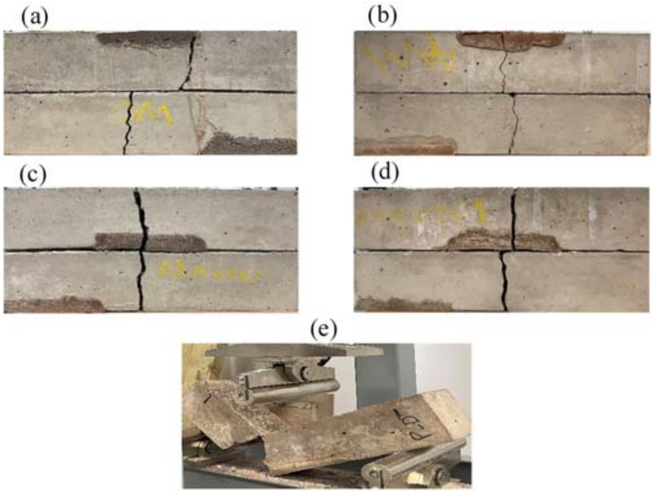

Fig. 6 Failure modes of the center- (top beam) and corner-repaired (bottom beam) beams in flexure: (a) repaired by ordinary mortar, (b) repaired by AA mortar, (c) repaired by WTRAA1 mortar, (d) repaired by WTRAA2 mortar, (e) pre-loaded and repaired by ordinary mortar

TABLE IV
MEAN FLEXURAL STRENGTH AND FAILURE MODES FOR THE CENTER-REPAIRED BEAMS

Repaired/undamaged Beam	Mean Flexural Strength (MPa)	Mean Compressive Strength Ratio	Mean Elastic Modulus Ratio	Mean Flexural Strength Ratio	Failure Mode
Undamaged	4.68	-	-	-	Center
Ordinary	4.69	0.64	0.64	1.00	Corner
Ordinary, pre-loaded	4.70	0.64	0.64	1.00	Corner
AA	4.89	0.60	0.68	1.05	Center
WTRAA1	5.20	0.30	0.41	1.11	Center
WTRAA2	5.51	0.26	0.40	1.18	Center

The beams repaired by the AA mortars have a flexural strength ratio of slightly higher than 1, and their compressive strength and elastic modulus ratios are less than 1 (see Table IV). These beams failed at the center of the repair material (see Fig. 1 (b)), which shows compatibility of the repair. The beams repaired by the WTRAA1 and WTRAA2 mortars have far lower compressive strength and elastic modulus ratios due to the presence of rubber particles in the mortar (see Table IV). The WTRAA1 and WTRAA2 mortars give flexural strength ratios much greater than 1. They increase the flexural strength of the repaired beam by 11% and 18%, respectively. The higher flexural strength ratio of the beams repaired by the WTRAA2 mortar can be attributed to its smaller rubber size. Both beams fail in the center of the repair mortar (see Figs. 6 (c) and (d)), which means it is a compatible failure. Thus, despite reduction in compressive strength, the WTRAA1 and WTRAA2 mortars demonstrate higher flexural strength ratios (see Table IV). This means that regardless of the type of failure mode, the repair is compatible. This desirable performance appears to be related to high ductility and strong bonding generated by slag and sodium hydroxide [23].

Further, the elastic modulus ratios of the beams repaired by ordinary mortars are less than 0.7, and hence incompatible repair and in complete agreement with previous studies [7], [13]. However, the AA, WTRAA1 and WTRAA2 mortars are compatible, even with elastic modulus ratios of far less than 0.7. The high ductility and flexibility of the mortars might delay the mortar's failure, and lead to a compatible repair. Further, the low compressive strength and low modulus of elasticity of the AA, WTRAA1 and WTRAA2 mortars contradict BS EN 1504-3, which recommends a mortar with minimum compressive strength of 45 MPa and modulus of elasticity of more than 20 GPa (Class R4) [29]. However, they provide higher flexural strength ratios, which make the repair compatible [14].

The corner-repaired beams are intended to check bonding and delamination at the concrete-mortar interface (see bottom beams in Figs. 6 (a)-(d)). The location of the repaired beams' failure is around the center, and their flexural strength values are nearly identical to the undamaged beam (see Table V). As the flexural strength at the corner of the damaged beam is smaller compared to the beam's center, the failure at the center suggests that the repair mortars should have not been delaminated from the beams. As a result, if the bonding between the repair mortar and the substrate concrete was insufficient, the beam would have failed at the left edge of the corner repair.

TABLE V
MEAN FLEXURAL STRENGTH TEST RESULTS FOR THE CORNER-REPAIRED BEAMS

Repaired/undamaged Beam	Mean Flexural Strength (MPa)	Mean Flexural Strength Ratio	Failure Mode
Undamaged	4.68	-	-
Ordinary	4.60	0.98	Center
AA	4.91	1.05	Center
WTRAA1	4.86	1.04	Center
WTRAA2	4.80	1.02	Center

IV. CONCLUSIONS

This study addresses the potential use of WTRAA mortars in repair of concrete structures through an experimental program. Concrete beams are created, damaged, and repaired by various types of mortars.

It is found that despite having very low compressive strength, the WTRAA mortars increase flexural strength of the repaired beams, exhibit a compatible failure, and provide adequate interface bonding. It is also seen that using higher amount of powder rubber improves flexural strength of the repaired beams. This shows that ductility and flexibility of the mortar might be an influential factor in achieving more compatible repairs for concrete structures. Further, it is seen that pre-loading does not affect the flexural strength of the repaired beams and their compatibility.

Although this study shows promising potential use of WTRAA mortars in repair of concrete structures and paves the way for research on this type of repair mortar, further studies can focus on large-scale reinforced concrete (RC) beams repaired with WTRAA mortars. Particularly, the authors are currently planning to perform large-scale experimental tests on RC beams repaired with WTRAA mortars to assess the effects of the mortar ductility and flexibility on its compatibility with concrete, and quantify the bonding between the mortar and concrete.

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