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Some aspects of the suitability of three-stage mixing for ready-mixed concrete

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Research Paper

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Some aspects of the suitability of three-stage mixing for ready-mixed concrete

Several studies have indicated that three-stage mixing (TM) methods improve the mechanical strength and slump of concrete compared to those of normal mixing methods, particularly when a recycled concrete aggregate is used. However, most studies did not address the technological aspects of ready-mixed concrete, including continuous mixing during site delivery. In this study, the properties of concrete (slump and compressive strength) based on the time lapse after mixing via the TM method (i.e. immediately, 45 min, and 90 min after mixing) were investigated, and the samples were tested after three years of curing. The results indicate some positive effects of TM on ready-mixed concrete and its characteristics on a delivery to the construction site, particularly a less severe loss of consistency compared to that of conventional mixing, as well as a positive effect on the compressive strength when fly ash is used as an aggregate coating additive in the first stage of concrete mixing.

Key words:

concrete, recycled concrete aggregate, three-stage mixing, mixing time, consistency, compressive strength

Prethodno priopćenje

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Aspekti prikladnosti trostupanjskog miješanja gotove betonske smjese

Nekoliko je istraživanja pokazalo da, u usporedbi s uobičajenim metodama miješanja, metode trostupanjskog miješanja (TM) poboljšavaju mehaničku čvrstoću i slijeganje betona, osobito kada se primjenjuje reciklirani betonski agregat. Međutim, većina istraživanja nije se bavila tehnološkim aspektima gotove betonske smjese, uključujući kontinuirano miješanje tijekom isporuke na gradilište. U ovom su istraživanju ispitivana svojstva betona (konzistencija slijeganjem i tlačna čvrstoća) na temelju vremenskog odmaka nakon miješanja metodom TM (tj. odmah, 45 min i 90 min nakon miješanja), a uzorci su ispitani nakon tri godine njege. Rezultati upućuju na neke pozitivne učinke metode TM na gotovu betonsku smjesu i njezine karakteristike pri isporuci na gradilište, točnije manji gubitak konzistencije u usporedbi s uobičajenom metodom miješanja, kao i pozitivan učinak na tlačnu čvrstoću pri primjeni letećeg pepela kao dodatka vezivu u prvoj fazi miješanja betona.

Ključne riječi:

beton, reciklirani betonski agregat, trostupanjsko miješanje, vrijeme miješanja, konzistencija, tlačna čvrstoća

1. Introduction

Concrete sets from a fluid to a solid over time, and therefore, a clear difference exists in properties between mixtures made immediately after mixing in an environmentally controlled laboratory and plant and those made on-site after being transported to the construction site [1]. In many cases, concrete is used as ready-mixed concrete mixed from batch plants to construction sites; therefore, from a practical engineering viewpoint, the time-dependent properties of concrete must be considered.

The main properties of concrete include workability and compressive strength. Among these, a prolonged mixing time did not negatively affect the compressive strength. Al-Negheimish and Alhozaimy [2] reported that the compressive strength of concrete produced onsite is slightly higher than that produced in a batching plant. Erdogdu [3] reported that the compressive strength of concrete 150 min after mixing increased by 15 % compared with that of concrete made immediately after mixing. Kırca et al. [4] also monitored the effect of prolonged mixing for up to 4 h, during which concrete was continuously mixed at low speeds. The presented strength values indicate an increase in the compressive strength of concrete of up to 27 % compared to concrete made immediately after mixing because the increased temperature inside the drum caused by the continuous mixing and agitation of concrete during transportation accelerates the hydration of cement and increases the evaporation of free water from concrete.

However, in contrast to the effect on compressive strength, a prolonged mixing time causes a serious loss of workability. Al-Negheimish and Alhozaimy [2] reported that the concrete slump decreased by 37 %, and its temperature increased by 1.1 °C during transport in the summer. Vickers et al. [5] shows that the slump of concrete mixed for 67 min was 60–75 % lower than the initial slump after mixing for 7 min. Mahmood et al. [6] indicated that the slump of concrete containing fly ash (FA) after 90 min was 32 % lower than that of concrete immediately after mixing. Further, it has been observed that a prolonged mixing time causes slump loss regardless of the dosage and type of superplasticiser [3, 7]. Retempering by adding water and a superplasticiser can restore the workability of concrete to its initial level to compensate for this slump loss. However, these methods decrease the mechanical strength and durability of concrete. Baskoca et al. [8] concluded that, although a prolonged mixing time had a minimal effect on the compressive strength, the compressive strength of concrete decreased by up to 35 % when retempering with additional water to restore the workability to the initial level because of the increased water-to-cement ratio.

Another issue concerning the use of recycled aggregates (concrete or brick) for producing concrete for practical use. Malešev et al. [9] reported that the strength and durability properties of concrete containing recycled concrete aggregate (RCA) are worse than those of concrete containing the natural aggregate (NA). The effect of recycled aggregate on concrete properties is analysed in detail by Baričevič et al. [10]. A main feature is a presence of microcracks and pores in the original adhered mortar attached to the RCA, which is a factor of quality deterioration that increases water absorption and decreases density compared with that of NA. The high-water absorption of RCA was responsible for the increased slump loss over time, as well as the lower slump and strength of recycled aggregate concrete (RAC). Therefore, researchers developed and proposed various mixing methods for improving workability in the fresh state, and the mechanical properties and durability in the hardened state of RAC. Tam et al. [11] proposed a two-stage mixing approach (TSMA). Unlike the normal mixing (NM) method wherein all materials are added at once, half of the mixing water is added to the RCA and cement to form a thin slurry layer on the surface of the RCA to fill cracks and voids in the TSMA, and the other half of the mixing water is subsequently added to complete the concrete mixing. The thin slurry layer formed on the RCA surface improved the interfacial transition zone (ITZ) between the RCA and new cement paste. Kong et al. [12] developed a three-stage mixing (TM) method to further improve ITZ by coating the RCA surface with pozzolanic materials and reported that the compressive strength of concrete made using the TM method was ~20 % higher than that of concrete mixed using TSMA. Li et al. [13] proposed a method in which a portion of water and pozzolanic materials were first mixed to form a slurry, and then, RCA was added to coat the surface with the slurry. The mixing methods presented here are related to the materials and application of the coating layer during the mixing process [11–16].

These studies suggest the importance of a coating method that improves the workability and mechanical properties of RAC. However, most studies are yet to address the technological aspects of ready-mixed concrete, including continuous mixing during site delivery. Apart from the previous studies by one of the authors [1, 17], the authors found no research on the complex effects of prolonged mixing on the consistency and compressive strength of TM-mixed concrete. Thus, this study investigated the properties of concrete (slump and compressive strength) based on the time lapse after mixing using the TM method (immediately, 45 min, and 90 min after mixing).

This research is unique because it monitors the long-term strength development of concrete ranging from two days to three years, which is valuable for understanding the effect of TM. Subsequently, the TM method was applied to the NA for comparison with the RCA (researchers only include the RCA when presenting the TM method). Finally, recycled concrete powder (RP) is used as a coating material, which is considered difficult to recycle and has therefore been studied minimally.

The presented research can be understood in terms of the quality control processes of concrete at the construction site and differences between samples produced in the concrete plant and those produced after delivery to construction sites.

2. Materials and methods

2.1. Mixing course

TM was used for improving the properties of the RAC. The configuration presented in this study was designed with the following features.

First mixing stage: Only coarse aggregates were coated on both the NA and RCA. Water (W_{ef1}) was added to dry coarse aggregates in amounts corresponding to the water absorption of coarse aggregates. Dry coating materials were added to wet coarse aggregates at a water-to-binder (w/b) ratio of 0.5, where a coating layer was formed on the surface of the coarse aggregates. The amount of coating material was calculated to form a layer thickness of 150 μm during this mixing stage. A classic method called the Kennedy method [18] was used for the calculations. This method enables calculating the amount of binder paste required to cover grains separately and the amount to fill the remaining voids by applying a layer thickness model based on the theory that the same thickness δ is formed on grains of different sizes. Various hypotheses for quantifying the cement paste layer covering the grains were presented in [19], as illustrated in Fig.1.

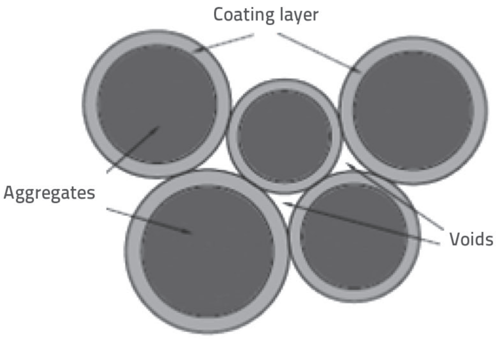


Figure 1. Model of the aggregate with a δ-thick coating layer that has empty voids [19]

For this experiment, the thickness of the coating layer was selected based on boundary conditions obtained by Poon et al. [20], who suggested 36–60 μm as a typical ITZ thickness in recycled aggregate concrete , and Li et al. [13], who presented a thickness of 500 μm to cover the entire ITZ. The volume of paste for coating the coarse aggregate *Vcp* (m³) was calculated as a multiple of the aggregate surface area *F* (m²) and layer thickness δ (μm). The surface area of the aggregate was calculated using [18]:

$$F = f \cdot \frac{\rho_b}{\rho_p} \sum \frac{p_i}{0{,}1 \cdot d_i} \quad (1)$$

The surface is characterised by the quality of the aggregate surface (f), loose bulk density, particle density of the aggregate (ρ_b and ρ_p, respectively, [kg/m³]), particle size distribution of the actual aggregate based on p_i (the amount of aggregate with an average grain size d_i [%]), and the average grain size of the aggregate fraction d_i [mm] parameters. Specific materials were used as coating materials: fly ash (FA) and recycled concrete powder (RP). Further, Portland cement was applied to have a standard binder for comparison with the other two coating materials and the concrete of a standard composition with no additives, with the cement divided into only two parts in terms of the TM process. Fine aggregates and cement were added during the second mixing stage. In the third mixing stage, water (W_{ef2}) mixed with a plasticiser was added to complete the concrete mixing. The amounts of cement and water required to fill the remaining voids between grains of coated aggregates were calculated using w/b = 0.5.

2.2. Materials and mixtures

Natural aggregates (NA) with a density of 2650 kg/m³ and recycled concrete aggregates (RCA) with densities of 2200

Table 1. Mix proportions of concrete

Component [kg/m³]			Concrete compositions according to the type of coarse aggregate and coating material					
			RCA_C	RCA_{FA}	RCA_{RP}	NA_C	NA_{FA}	NA_{RP}
Aggregates	NA	0/4	898	898	898	896	896	896
		4/8	-	-	-	269	269	269
		8/16	-	-	-	627	627	627
	RCA	4/8	224	224	224	-	-	-
		8/16	545	545	545	-	-	-
	Volume [m³]		0.676					
	Volume [%]		67.6					
Paste to coat aggregates	Coating material		80	68	68	55	47	47
	Water [W_{ef-1}]		39.8	33.8	33.8	27.4	23.2	23.2
	Volume [m³]		0.046					
	Volume [%]		4.6					
Paste to fill voids	CEM I 42.5 R		310	310	310	336	336	336
	Water [W_{ef-2}]		155	155	155	168	168	168
	Volume [m³]		0.278					
	Volume [%]		27.8					
Admixture			2.5	2.5	2.5	2.7	2.7	2.7

kg/m^3 (4/8) and 2300 kg/m^3 (8/16) were obtained from a construction and demolition waste recycling company. Cement CEM I 42.5 R (C) was used as a basic binder to mix components in the second and third mixing steps and as a coating material in the first mixing step. As alternative coating materials, FA obtained from the energy sector of a steel-making factory [grain size d(0.9) = 95 μm] and RP obtained by the separation of recycled concrete fines smaller than 125 μm were used. The RP was applied to use a fine portion of RCA, which is otherwise difficult to recycle in concrete production. Finally, a polycarboxylate plasticiser was used.

As control samples, mixtures with only NA and mixtures produced by standard mixing (i.e. NM) were prepared and tested. The coating materials were added simultaneously with a basic binder (cement) when applying NM. The mix proportions are listed in Table 1.

Six different concrete composites that varied according to the type of aggregate (RCA and NA) and coating material (FA, RP, and C) were prepared (Table 1). Cube specimens with 100 mm dimensions were made at the following time intervals for determining the effect of discharge time on the compressive strength of concrete: immediately after mixing (0'), after 45 min (45'), and after 90 min (90'). Each concrete mixture was remixed every 15 min while waiting for discharge and the casting of the specimens. The cubes were cured under standard conditions for the testing time. A standard slump test according to EN 12350-2 [21] was conducted for fresh concrete, and a compressive strength test according to EN 12390-3 [22] was conducted after 2, 28, and 90 days and 3 years of setting and hardening.

3. Results

3.1. Consistency

Slump values for individual measurement times are presented in Figures 2 (RCA concrete) and 3 (NA concrete). Variations in consistency (presented as percentages) are listed in Table 2. For all samples, a loss of consistency was observed with prolonged mixing, which is a common result reported in other studies [3, 23]. Average values of the consistency loss by aggregate type and mixing method are outlined as follows: average loss of the consistency of mixtures with *RCA*: 34 % (45') and 55 % (90'); average loss of the consistency of mixtures with *NA*: 16 % (45') and 34 % (90'); average loss of consistency of mixtures prepared by the *TM method*: 13 % (45') and 34 % (90'); and average loss of consistency of mixtures prepared by the *NM method*: 37 % (45') and 56 % (90').

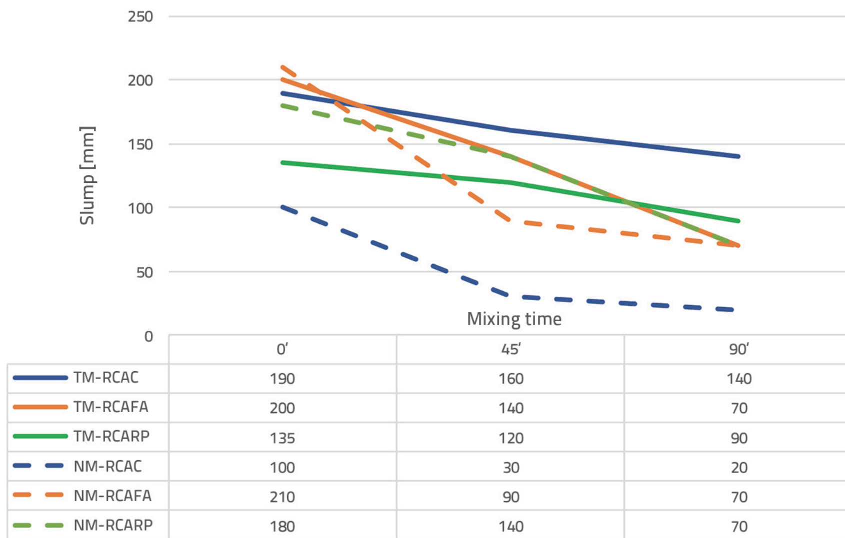


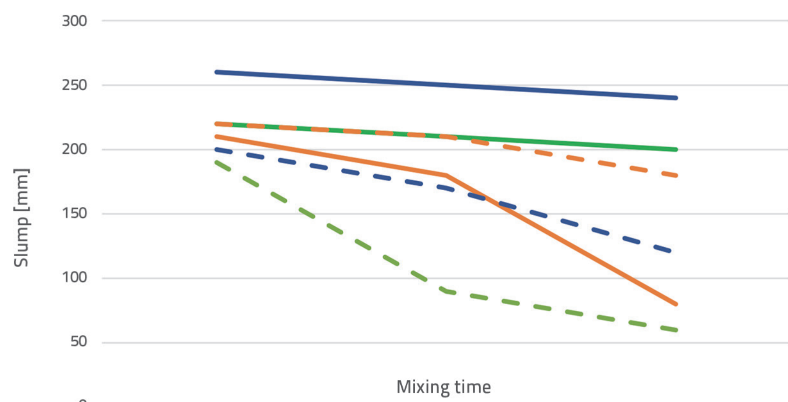
Figure 2. Slump results for samples prepared using RCA

Table 2. Change in the consistency of samples caused by prolonged mixing

Sample	Change of consistency [%]		Change of slump class
	0'/45'	0'/90'	0'/90'
TM - RCA$_C$	-16	-26	S4/S3
TM - RCA$_{FA}$	-30	-65	S4/S2
TM - RCA$_{RP}$	-11	-33	S3/S2
TM - NA$_C$	-4	-8	S5/S5
TM - N$_{AF}$A	-14	-62	S4/S2
TM - NA$_{RP}$	-5	-9	S5/S4
NM - RCA$_C$	-70	-80	S3/S1
NM - RCA$_{FA}$	-57	-67	S4/S2
NM - RCA$_{RP}$	-22	-61	S4/S2
NM - NA$_C$	-15	-40	S4/S3
NM - NA$_{FA}$	-5	-18	S5/S4
NM - NA$_{RP}$	-53	-68	S4/S2

RCA-based concrete (Figure 2): As demonstrated by our results (69 % on average after 90' of mixing) and presented in [24] NM relates to the high loss of the consistency of concretes with RCA; here, a loss of consistency (28–37 %) after 90' of NM of concretes with 20–100 % of RCA was reported. This is illustrated in Fig. 2. TM helps obtain better consistency when CEM is used as a coating material. This effect applies to the slump immediately after mixing the concrete and the slump after prolonged mixing. Further, TM maintain consistency in mixing time because the reduction in the consistency values of samples prepared by TM and NM after 90' of mixing are 26 and 80 %, respectively. Samples with FA coating achieved better consistency with TM up to 90', with almost the same loss of consistency after 90' of mixing, whereas TM achieves better consistency for samples coated with RP after only 90' of mixing. The improved consistency, as well as the smaller loss of consistency of the samples prepared by the TM, is attributed to coating rough surfaces of the RCA with powdered materials during the first stage of mixing, which results in a more uniform and smoother grain surface. Simultaneously, the formed layer prevents the penetration of water added during the second phase of mixing into the RCA grains, thereby eliminating a major shortcoming of RCA (high water absorption), which left sufficient mixing water to achieve and maintain consistency.

NA-based concrete (Figure 3): NM resulted in a loss of concrete consistency with 100 % NA, as demonstrated by our results (42 % on average after 90' of mixing), as well as by those in [24] (52 %). Fig. 3 shows that TM positively affected the consistency of concrete with CEM and RP as coating materials, which was applied to the immediate slump as well as to that during prolonged mixing. Further, as reductions in consistency values of samples prepared by TM were 8 % and 9 %, TM maintained consistency in mixing time, whereas they were 40 and 68 % for those prepared by NM, respectively. The triple mixing of samples with FA was not effective. Comparing the average values of all samples (shown above), TM produced less loss in consistency than that of NM. This effect was applied individually to all sample pairs except for the NA-based samples coated with FA (TM-NA_{FA}/NM-NA_{FA}). Here, the loss of consistency caused by prolonged mixing is higher with the TM approach (14 % – 45', 62 % – 90') compared to that wiwth the NM approach (5 % – 45', 18 % – 90').
Covering the aggregate with paste before adding other ingredients to complete the concrete mixing is advantageous for controlling the consistency of finished concrete over time, compared to that with NM. The results for NM with a stronger loss of consistency after 90' are consistent with the findings of Erdogdu et al. [3]. The concrete subjected to prolonged mixing results in a relatively rapid slump loss up to 90 min of mixing, which indicates that a mixing period of 90 min appears to be a turning point for the appropriate placement, compaction, and subsequent operations of concrete.
Table 2 lists slump classes of each concrete for basic mixing (0') and 90' concrete mixing according to [25]. Some mixtures showed that the slump class of concrete mixed for 90' is up to two grades lower than that of concrete mixed for 0', which is a turning point for the appropriate placement, compaction, and subsequent operations of concrete [3, 5, 6]. Among the six series of concrete prepared with TM and NM, two series of concrete prepared with TM (TM – RCA_{FA} and TM – NA_{FA}) and four series of concrete prepared with NM (NM – RCA_{CEM}, NM – RCA_{FA}, NM – RCA_{RP}, and NM – NARP) decreased by two grades. Therefore, TM appeared to be more favourable to maintain consistency for up to 90 min.
The greatest changes associated with TM are related to the coating of aggregates with FA (TM – RCA_{FA} and TM – NA_{FA}). The loss of consistency in concrete blended with FA during longer mixing times was reported in [23]. In the study, concrete mixes with 20 % FA (which is roughly the case in this research) have a residual slump (after 90' of agitating) of ~50 % of the initial slump. Mahmood et al. [6] found that the slump of concrete containing FA after 90 min was 32 % lower than that of concrete immediately after mixing. Our results indicate a 38 and 35 % residual slump for NA and RCA, respectively. However, these circumstances are compensated for by the properties of hardened concrete, where TM is favourable for samples blended with FA.



	0'	45'	90'
TM-RCAC	260	250	240
TM-RCAFA	210	180	80
TM-RCARP	220	210	200
NM-RCAC	200	170	120
NM-RCAFA	220	210	180
NM-RCARP	190	90	60

Figure 3. Slump results for samples prepared with NA

3.2. Compressive strength

Table 3 presents results for the compressive strengths of all prepared concretes at various ages. From the viewpoint of concrete testing methodology in practice, concrete specimens cast after the basic mixing process are considered to be produced in batching plants, and the specimens cast after longer mixing are considered as being produced on-site.
The significance limit was expressed for each sample age to assess the significance of changes in compressive strength caused by prolonged mixing. A typical difference of one strength class as characterised in EN 206+A2 [25], (i.e. 5 MPa), was considered a criterion and expressed as a percentage of the

Table 3. Compressive strengths of samples at different ages and mixing times

Sample	f_c – compressive strength [MPa]											
	2 days			28 days			90 days			3 years		
	0'	45'	90'	0'	45'	90'	0'	45'	90'	0'	45'	90'
TM - RCA_C	18.3	17.4	16.1	37.0	34.4	34.8	43.8	38.3	40.8	47.0	39.4	44.1
+/- between 0'/90'	-12 %			-6 %			-7 %			-6 %		
TM - RCA_{FA}	13.4	13.4	12.7	27.7	29.2	30.3	37.8	40.2	39.0	47.8	47.6	48.5
+/- between 0'/90'	-5 %			+9 %			+3 %			+2 %		
TM - RCA_{RP}	11.7	10.6	11.4	25.6	22.2	24.4	31.3	28.9	29.2	32.0	30.7	33.8
+/- between 0'/90'	-3 %			-5 %			-7 %			+6 %		
TM - NA_C	19.4	19.4	19.6	37.0	35.3	34.8	45.7	43.7	40.2	67.2	65.0	66.3
+/- between 0'/90'	+1 %			-6 %			-12 %			-1 %		
TM - NA_{FA}	17.6	18.6	19.0	38.2	39.9	41.7	51.1	51.1	54.8	52.6	54.3	57.6
+/- between 0'/90'	+8 %			+9 %			+7 %			+10 %		
TM - NA_{RP}	15.7	15.9	16.5	34.1	32.5	32.3	39.4	39.3	38.6	40.0	39.3	40.8
+/- between 0'/90'	+5 %			-5 %			-2 %			+2 %		
NM - RCA_C	16.2	17.1	17.6	24.9	27.2	28.1	32.3	34.0	37.1	31.5	32.8	35.5
+/- between 0'/90'	+9 %			+13 %			+15 %			+13 %		
NM - RCA_{FA}	13.2	13.9	14.1	34.4	35.4	36.3	37.9	39.8	40.3	40.0	42.7	42.9
+/- between 0'/90'	+7 %			+6 %			+6 %			+7 %		
NM - RCA_{RP}	12.7	12.4	12.6	33.8	33.7	34.3	40.1	42.6	41.2	37.7	39.3	38.2
+/- between 0'/90'	-1 %			+2 %			+3 %			+1 %		
NM - NA_C	20.8	20.9	20.3	42.9	40.7	39.3	48.3	45.5	50.9	48.2	50.2	52.1
+/- between 0'/90'	-2 %			-8 %			+5 %			+8 %		
NM - NA_{FA}	18.4	18.5	18.3	37.7	37.7	34.9	49.3	47.7	48.5	47.9	48.7	50.4
+/- between 0'/90'	-1 %			-7 %			-2 %			+5 %		
NM - NA_{RP}	19.4	19.6	21.8	39.3	41.4	43.3	45.9	46.2	48.0	42.2	42.3	44.0
+/- between 0'/90'	+12 %			+10 %			+5 %			+4 %		

average strength of samples produced immediately after mixing (control samples, 0'). For example, the significance level of changes in compressive strength for two-day samples was 30 % (5 MPa from 16.4 MPa). The authors are aware that such an assessment is only relevant for samples aged 28 d, for which the strength class specification applies by default; the assessment of samples of other age groups should only be considered a guide. The significance level is indicated by a red line in Figures 4–7, which shows changes in compressive strength because of prolonged mixing for different aggregate types, mixing times, and sample ages. The selected angle of view indicates that, except for three values for TM and two values for NM, all changes in strength caused by prolonged mixing are insignificant because they do not even represent a difference in one strength class.

3.2.1. Analysis of relative strength changes for RCA concretes

Further analysis was performed based on the type of aggregate used in concrete production. For RCA concretes, no noticeable differences exist in increases/decreases between 0' and 45' (Fig. 4), as well as between 0' and 90' (Fig. 5). The variation remained after 90 min of mixing if an increase/decrease in the compressive strength occurred after 45 min.

Relative to time 0', samples prepared by the TM method showed a decrease in strength after 45' of mixing (Fig. 4) and after 90' (Fig. 5), with strengths after 90' being higher than that after 45'. Thus, the strength increases again but does not reach the initial strength of the samples with longer mixing times. The decrease in strength is not significant, and it exceeds the significance level

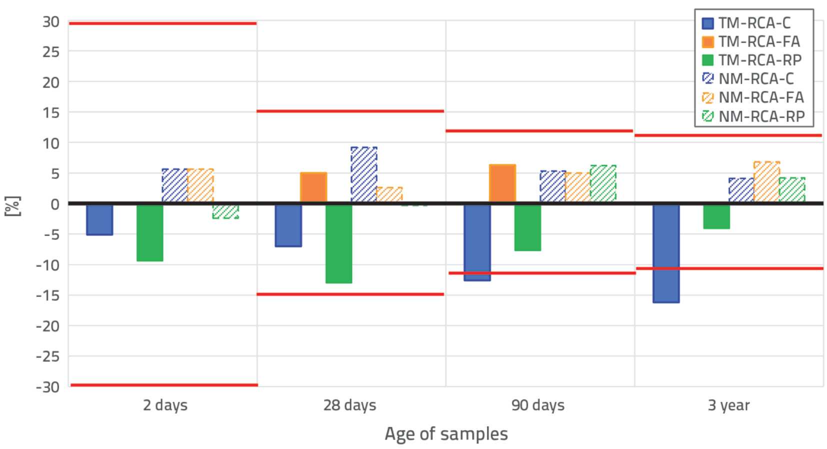


Figure 4. Comparison of changes in compressive strength for RCA concretes and 45′ of prolonged mixing. The red lines indicate the significance level for each age group

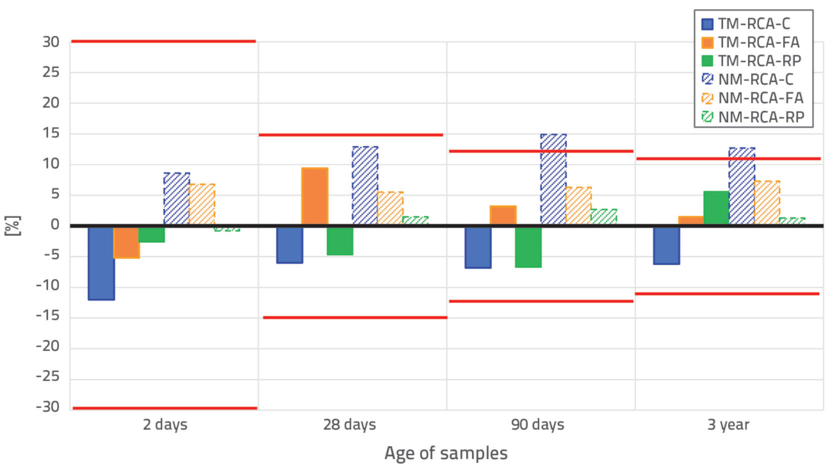


Figure 5. Comparison of changes in the compressive strength of RCA concretes and 90′ of prolonged mixing. The red lines indicate the significance level for each age group

only for CEM as a coating material after 45′ mixing, i.e. at 90 days (12 % decrease) and 3 years (16 % decrease). The exception is a sample with a FA coating material, whose strength increases smoothly with mixing time; however, this increase in strength does not reach significance. Maximum values of the increase are 6 % after 45′ of mixing (samples aged 90 days) and 9 % after 90′ (samples aged 28 days). Therefore, the type of coating material is important when concrete mixed with TM is subjected to additional mixing. The authors believe that this is affected by the better stability of FA coating paste on the grain surface when comparing CEM and RP pastes with the same w/c ratio. According to [12], FA acts as a microfiller, filling the ITZ between the aggregate surface and bulk cement matrix, followed by a pozzolanic reaction in the same place. A thin layer of pozzolanic particles was coated around the RA during the first mixing stage using the TM. During concrete hardening, this layer improves the ITZ through the filler and pozzolanic reactive effects.

All samples prepared using NM showed an increase in strength with an increase in mixing time, whereas values of the samples prepared using FA and RP were considered negligible. Comparing other coating materials, samples with CEM showed better results in most cases, while 45′ after mixing, they achieved values up to 9 % (28 days), and after 90′ mixing, they achieved an increase of 13 (28 days and 3 years) and 15 % (after 90 days), almost reaching or even exceeding the significance level (Fig. 4). The positive effect of prolonged mixing persisted as the sample aged, i.e. up to three years of testing, RP appeared to tend towards positive manifestations with age. As demonstrated by Poon et al. [26], the <0.15 mm fraction of RCA probably causes self-cementing properties because this fraction of RCA contains the highest amount of C2S. With actual particles of <12.5 mm, this effect was confirmed when a hardening coating layer was formed around RCA grains.

3.2.2. Analysis of relative strength changes for NA concretes

For NA concretes, samples that showed an increase in strength after 45′ mixing have even higher strength values after 90′ mixing. This applies, for example, to TM-NA-FA and NM-NA-RP (28 days), or all samples except TM-NA-CEM aged three years. The strength increased with an increase in mixing time, which is consistent with other studies that attribute this effect to reduced air content in addition to the beneficial effect of appropriate placement and compaction of concrete [2, 3], or to an increased temperature inside the drum caused by continuous mixing, which accelerates the hydration of cement and increases the evaporation of free water from concrete [4]. Erdogdu et al. [23] found a strength gain for samples with FA after 90′ of agitation ranging from 15–20 % on average.

Relative to time 0′, samples prepared by the TM method show a decrease in strength after 45′ (Fig. 6) and 90′ of mixing (Fig. 7). Strengths after 90′ are higher than those after 45′ only for samples aged three years. However, the decrease in strength is not significant and exceeds the significance level only for CEM as a coating material after 90′ mixing, namely, at 90 days (12 % decrease).

The exception is the sample with the FA coating material, whose strength, in principle, increases with mixing time; however, this strength increase does not reach the significance level. The positive effect of the prolonged mixing of this mixture persisted

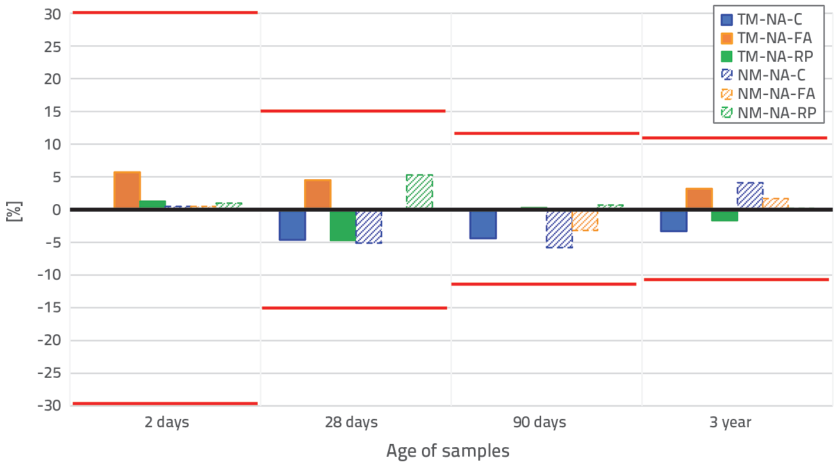


Figure 6. Comparison of changes in the compressive strength for NA concretes and 45' of prolonged mixing. The red lines indicate the significance level for each age group

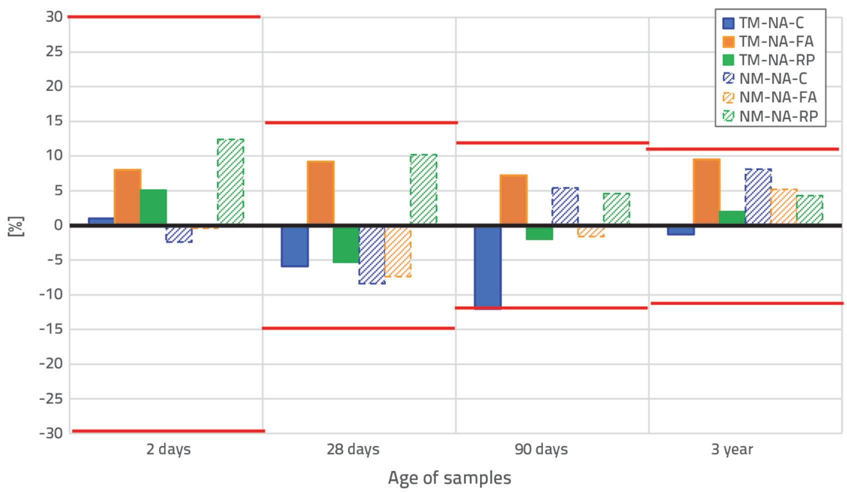


Figure 7. Comparison of changes in compressive strength for NA concrete and 90' of prolonged mixing. The red lines indicate the significance level for each age group

throughout the test age of the samples, i.e. up to three years of testing, with a maximum increase of 9 %. Thus, the type of coating is important when concrete mixed with TM is subjected to additional mixing when using NA.

NM samples did not provide uniform results as RCA samples for the effect of prolonged mixing on samples of different ages. For samples with cement and FA, prolonged mixing caused a reduction in strength up to 90 d of concrete age; however, after three years of curing, the strength of the samples increased. Samples with cement mixed for 90' show this tendency earlier (from 90 days of curing). The positive effect of prolonged mixing was evident when RP was used as the coating material, with a tendency to decrease in strength with the age of the samples.

4. Conclusion

This study investigated the properties of concrete (slump and compressive strength) based on the time lapse after mixing using the TM method (i.e. immediately, 45 min, and 90 min after mixing). Samples mixed with both NA and RCA were tested after three years of curing. Prolonged mixing does not have a significant effect (either positive or negative) on the compressive strength of concrete (applied to both methods of mixing: NM and TM) when analysing the compressive strength results and considering the value of one strength class as a criterion. This can also be applied to concrete quality control processes at manufacturing and construction sites. The difference in strength between samples produced by the manufacturer (immediately after mixing) and those produced after transport to the construction site (after 90 min of mixing) did not represent one strength class. This relates to discussions about which values are considered more authoritative. However, to distinguish the characteristics of TM-mixed concrete during prolonged mixing in more detail, we can state the following:

- The TM method provides a better initial consistency of concrete based on NA. For concrete containing RCA, this applies only if the cement is used as the coating material.
- The TM method resulted in a smaller loss of consistency with prolonged mixing than that with the NM method. Therefore, TM are recommended to help chemical admixtures maintain consistency if required on-site because the possible negative effect (depending on the actual concrete composition) on the compressive strength is negligible.
- For the compressive strength, the type of coating material is important when concrete mixed with TM is subjected to additional mixing. An increase in the compressive strength after prolonged mixing is observed when the TM method appears to be advantageous when FA is used as a coating material for both RCA and NA.
- However, based on the following maximal values, the strength increase in samples with the FA coating material is not significant.
  - For RCA-based concretes: 6 % after 45' of mixing (age of samples 90 days) and 9 % for 90' of mixing (age 28 days)
  - For NA-based concretes: 5 % after 45' of mixing (age of samples 28 days) and 9 % for 90' of mixing (age 28 days and 3 years)

- For ready-mixed concrete, the TM method demonstrated the following characteristics: Given that the extended mixing time is related to the delivery distance, increases in strength were observed with longer mixing times, and values after 90' mixing are better than those after 45'.
- RP is equivalent to other coating materials, and it has no noticeable negative effects on strength and indicates that the strength of TM-mixed concrete coated with RP improves in the long term.

Three-stage concrete mixing involves several variables and offers several possibilities for modification, each of which affect the final quality of the concrete. This relates to the choice of materials for the concrete and their relative proportions. The choice of material for the grain coating in the first stage of mixing and its quantity; the exact order of dosing the components; loading times, specifically the sequencing and loading of water; mixing time during each step and breaks between them; and intensity of mixing. Accordingly, the greatest research prospect currently appears to be the application of various secondary raw materials in concrete composition to study the effects of different process parameters on concrete properties and optimise the combination of process parameters.

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